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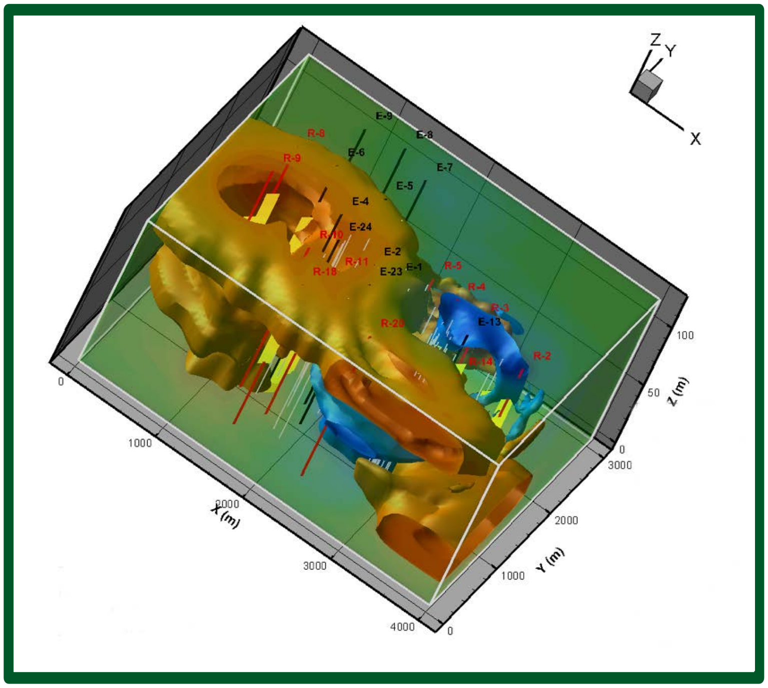

Cost-Effective and High-Resolution Subsurface Characterization Using Hydraulic Tomography

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ACRONYMS AND ABBREVIATIONS

2-D	Two-dimensional
3-D	Three-dimensional
ADEQ	Arizona Department of Environmental Quality
AFP44	Air Force Plant No. 44
bgs	Below ground surface
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CMT	Continuous multichannel tubing
CT	Computerized Tomography
DoD	Department of Defense
gpm	Gallons per minute
HT	Hydraulic Tomography
K	Hydraulic conductivity
ln	Natural logarithm
LZ	Lower Zone
m	Meters
m/s	Meters per second
MAP	Maximum a posteriori
NA	Not available
NCRS	North Campus Research Site
PW	Pumping well
RF	Random Field
RV	Random Variable
SLE	Successive Linear Estimator
SSLE	Sequential Successive Linear Estimator
SSHT	Steady-state Hydraulic Tomography
S_s	Specific storage
TIAA	Tucson International Airport Area
UW	University of Waterloo

UZ	Upper Zone
UZLU	Upper Zone Lower Unit
UZUU	Upper Zone Upper Unit

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EXECUTIVE SUMMARY

OBJECTIVE OF THE DEMONSTRATION

In many cases, especially at recalcitrant sites with complex hydrogeology, inaccurate or inadequate delineation of groundwater flow fields at appropriate resolution has resulted in poor remediation performance. Hydraulic conductivity (K) and specific storage (S_s) are the major parameters governing the fate and transport of contaminants in the subsurface. High-K zones and fractures are fast-flow conduits where transport of dissolved contaminants potentially poses significant threats to downgradient receptors. Low-K zones are potential repositories of contaminant mass that slowly release contaminants and contribute to long-term risks and liability. The overall objective of this project is to provide the Department of Defense (DoD) and its remediation contractors with the Hydraulic Tomography (HT) technology for delineating the spatial distribution of the K and S_s parameters in high resolution. Specific technical objectives are to: 1) demonstrate that HT is superior to conventional methods for estimating the spatial distribution of hydrogeologic properties; 2) illustrate that an HT survey can be readily conducted at DoD sites using existing networks of groundwater extraction/injection and observation wells; and 3) develop guidance for HT field implementation and compare costs associated with HT and conventional methods.

TECHNOLOGY DESCRIPTION

The HT concept is analogous to the Computerized Tomography (CT) scanning technology, which is based on combining a series of X-ray images taken from many different angles to make detailed pictures of the physiological structures inside a human body. HT involves sequentially conducting a series of aquifer hydraulic tests (HT survey). The hydraulic stresses in the subsurface are perturbed differently in each test, and the resulting potentiometric head changes over a well network are monitored. Each test is comparable to taking a snapshot of the aquifer heterogeneity at one angle, and the whole HT survey is analogous to hydraulically scanning the subsurface from many different angles. The complete data set of observed hydraulic head responses at multiple locations are jointly analyzed through a consistent mathematical model, which provides detailed spatial distribution of hydraulic properties of the aquifer, patterns of connectivity of highly conductive zones, locations of low conductive zones, and the uncertainties associated with the spatial distribution (HT analysis).

DEMONSTRATION RESULTS

The technical performance and cost-effectiveness of HT have been demonstrated at two field sites: (1) the University of Waterloo (UW) North Campus Research Site (NCRS), which is a local-scale site extensively instrumented at a spatial resolution critical to typical source zone remedial actions; and (2) the Air Force Plant No. 44 (AFP44) site, which is at a field-scale typical of DoD environmental sites with an existing pump-and-treat system and monitoring well network.

The results from the demonstrations at both sites confirmed that HT provides more accurate site characterization than conventional techniques. In the context of predicting hydraulic responses induced by other pumping tests, hydraulic property estimates from HT ambiguously outperform those of conventional models. The HT predictions are unbiased and have smaller errors and uncertainty.

The HT results are consistent with the current knowledge of the spatial distribution of the high-K and low-K permeable regions. The demonstration at the AFP44 site, where pump-and-treat remediation is on-going, illustrated that HT is cost-effective and can readily be applied at other sites with existing well networks and pump-and-treat systems. The only HT site characterization costs were the labor costs for conducting pumping tests and performing HT model inversion. HT is a “user-friendly” site characterization technology. The skills and equipment needed for conducting HT survey are the same as those commonly used in conventional site characterization. The input data required for model inversion by HT are the same as the data used in groundwater model development and calibration, such as the input data for parameter estimation using the commonly used software PEST and MODFLOW. Besides, HT delineates low-K zones consistent with the available local lithologic data. HT infers the hydraulic continuity of the low-K regimes in between available lithologic information. It provides information as to whether these regimes are hydraulically functioning as competent barriers. In conjunction with available existing chemical concentration data, HT is useful for evaluating potential residual sources.

IMPLEMENTATION ISSUES

If the on-site water treatment system is not available or not suitable for the extracted water from an HT survey, temporary storage and transportation options should be discussed, with consideration of the pumping rates and durations required for showing sufficient drawdown responses. If injection tests are required for the HT survey, a suitable source of injection water, such as clean or treated water, needs to be found and its transportation planned accordingly.

If additional wells are needed, and especially if they need to be installed in areas with high chemical concentration, pertinent regulatory approval and permits might be required. This is a similar issue with conventional well installation. If the HT pumping tests involve groundwater extraction, pumping permits might be required. In addition, permits for the discharge to the on-site or off-site treatment systems need to be acquired. Depending on the application process, extraction water sampling might be necessary. Similarly, permits might have to be obtained for water injection, with a potential sampling of the injection water.

The key factors to be considered in making a decision as to whether HT is appropriate for a site include cost-effectiveness, timing and duration, knowledge of background hydraulic stresses, and chemical mobilization. The cost-effectiveness depends on the appropriate number of wells, which is dictated by the spatial resolution needed to meet the objectives and whether existing wells and treatment system are adequate. If an existing well and treatment system can be utilized, the costs associated with HT is minimal.

In addition, water level changes due to HT pumping tests might cause chemicals to move during the tests. The duration of the pumping tests is usually short, and the amount of the associated chemical movement is typically small. However, if the aquifer is very permeable, a large pumping rate might be required to generate a measurable hydraulic response signal. On the other hand, if the aquifer is relatively less permeable, the well yield might be small, and a longer HT pumping test duration might be needed.

1.0 INTRODUCTION

Hydraulic Tomography (HT) is a high-resolution subsurface characterization technology for **delineating the spatial distribution of hydraulic conductivity (K) and specific storage (S_s)** parameters. These parameters are the major factors governing the fate and transport of contaminants in the subsurface, thus critically affecting the performance of remedial actions at environmental sites. The technical performance and cost-effectiveness of HT have been demonstrated in this project at two field sites. The first demonstration was performed at the **North Campus Research Site (NCRS)** located on the University of Waterloo (UW) campus in Canada. It is a local-scale site extensively instrumented at a spatial resolution critical to typical source zone remedial actions. The second demonstration was conducted at the **Air Force Plant No. 44 (AFP44) site** in Tucson, Arizona. It is at a field scale typical of Department of Defense (DoD) environmental sites. This site has an existing pump-and-treat system and monitoring well network.

1.1 BACKGROUND

Groundwater flow field is a critical factor dictating the transport of contaminants in the subsurface. It is highly dynamic and heterogeneous. Its spatial variation leads to contaminant dispersion. More importantly, **high-K zones** and fractures, such as buried gravelly stream channels, are fast-flow conduits where dissolved contaminants travel. These preferential pathways potentially pose significant threats to downgradient receptors. **Low-K zones**, such as clayey lenses, are potential repositories of contaminant mass that slowly releases contaminants due to back-diffusion. These residual sources contribute to long-term environmental risks and liability.

Especially at recalcitrant sites with complex hydrogeology, **inaccurate or inadequate delineation of groundwater flow fields has resulted in poor remediation performance**. Despite the best remediation efforts, these sites continue to be long-term environmental liabilities (NRC, 2013). Examples include: pump-and-treat systems failing to cost-effectively or efficiently contain contaminated groundwater; a chemical of concern migrating downgradient along unidentified pathways; an injected substrate not reaching targeted treatment zones or has insufficient residence time to enhance bioremediation; an impermeable barrier not fully intercepting contaminant migration pathways; or, a monitoring well network not installed at appropriate locations to collect useful information. Many pump-and-treat sites in the United States have been operated for more than fifteen years without achieving remediation goals. Operating and maintaining these systems is often costly. Many of them are now undergoing optimization and re-evaluation. Some of these sites are even in the process of considering a technical impracticability waiver application. Accurately depicting the subsurface hydrogeology in both contaminant source zones and dissolved plume areas is crucial for reliable assessments of potential risks to nearby receptors and for designing effective remediation systems. Therefore, subsurface characterization techniques that improve understanding of subsurface heterogeneity in high-resolution are critical for improving performance of existing systems and/or for developing alternative remedial action to achieve groundwater cleanup goals in a reasonable timeframe, thus resulting in substantial cost savings and risk reduction over the life cycle of the remediation program.

Conventional hydrogeological characterization techniques, such as borehole core or cuttings samples, generally provide local-scale geologic, lithologic, and/or hydrostratigraphic data at a few locations. Spatially interpolating or extrapolating this punctual information across the area of concern is subjective. In addition, this information does not directly provide hydraulic parameter values. Estimating the spatial distribution of K and S_s parameters based on this information is inherently uncertain. Although high-resolution information may be obtained using borehole sampling, it is invasive and cost-intensive, especially in deep formations.

Aquifer tests may be performed at a site. The results are commonly analyzed to estimate K and S_s-values using analytical solutions based on the simplified assumption that the aquifer is homogeneous and uniform (e.g., Theis' or Cooper-Jacob method). Such analyses yield equivalent properties that somewhat represent the typical properties between the pumping well and monitoring well within the cone of depression. **Geophysical methods** have increasingly been used to supplement conventional characterization by producing a high-resolution image of the subsurface. Although these methods can be relatively quick and inexpensive to perform, they only provide a high-resolution image of geophysical properties instead of hydrogeologic properties. Site-specific petrophysical relationships may have to be developed to translate the geophysical properties to corresponding hydrogeologic properties, leading to considerable uncertainty.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of this project is to provide the DoD and its remediation contractors with the HT technology for delineating the spatial distribution of the K and S_s parameters in high resolution. Specific technical objectives are to: 1) demonstrate that HT is **superior** to conventional methods for estimating the spatial distribution of hydrogeologic properties; 2) illustrate that an HT survey can be **readily** conducted at DoD sites using existing networks of groundwater extraction/injection and observation wells; and 3) develop **guidance** for HT field implementation and compare costs associated with HT and conventional methods.

1.3 REGULATORY DRIVERS

Regulations protecting water resources require environmentally impaired aquifers to be remediated to an acceptable condition. Sources and impacted zones might need to be contained to prevent further expansion of the contamination extent. The success of remedial action at a site in achieving clean-up goals, as well as the ability of a containment system to control contaminant migration, hinges upon whether groundwater flow field can be adequately delineated. HT is a technology for depicting the groundwater flow field at high resolution. Incorporating the results from HT in remediation and containment operations would **increase the reliability of remedial action and the chance of meeting regulatory requirements**.

2.0 TECHNOLOGY

HT is a new generation of hydraulic testing and analysis technology used to image the spatial distribution of the subsurface K and S_s parameters in high-resolution (K and S_s tomograms). The development of HT has been funded by SERDP over the past decade. HT has been validated in numerical experiments, controlled laboratory experiments, and field experiments.

2.1 TECHNOLOGY DESCRIPTION

2.1.1 Technology overview

The HT concept is comparable to a person viewing an object from different angles to gain more details of the geometry of an object. An example of this analogous concept employed in medical sciences is the Computerized Tomography (CT) scanning technology, which is based on combining a series of X-ray images taken from many different angles to construct detailed a three-dimensional (3-D) model of the physiological structures inside a human body.

HT involves sequentially conducting a series of aquifer hydraulic tests (**HT survey**). The **hydraulic stresses in the subsurface are perturbed differently** for each test, and the resulting potentiometric head changes over a well network are monitored. Each test is comparable to taking a snapshot of the aquifer heterogeneity, and the entire HT survey is analogous to hydraulically scanning the subsurface. The complete data set of **observed potentiometric head responses at multiple locations are jointly analyzed** through a consistent mathematical model, which provides detailed spatial distribution of hydraulic properties of the aquifer, patterns of connectivity of highly conductive zones, locations of low conductive zones, and the uncertainties associated with the spatial distribution (**HT analysis**). The HT technology is schematically illustrated in Figure 2-1.

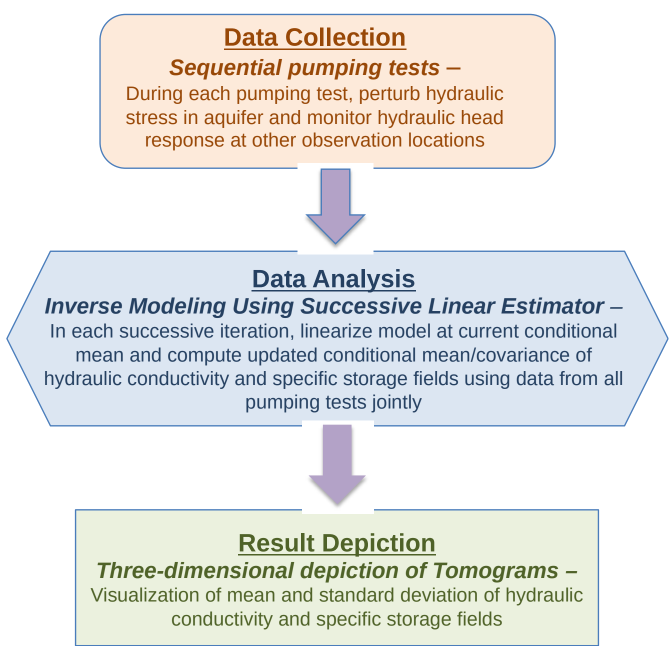

Figure 2-1. HT Concept

The novelty of the HT technology demonstrated in this study is the collection of non-redundant hydraulic information from different pumping tests in HT survey and the inclusion of all data in HT analysis without making a presumption of the form of spatial K and S_s distributions. It is different from the zonation and pilot point approaches that are commonly utilized to represent the spatial K and S_s distributions subjectively. Figure 2-2 shows an example of a 3-D distribution of a K-field delineated by HT. **The resolution of HT results depends upon the spacing of wells and the number of data collection ports along each well.**

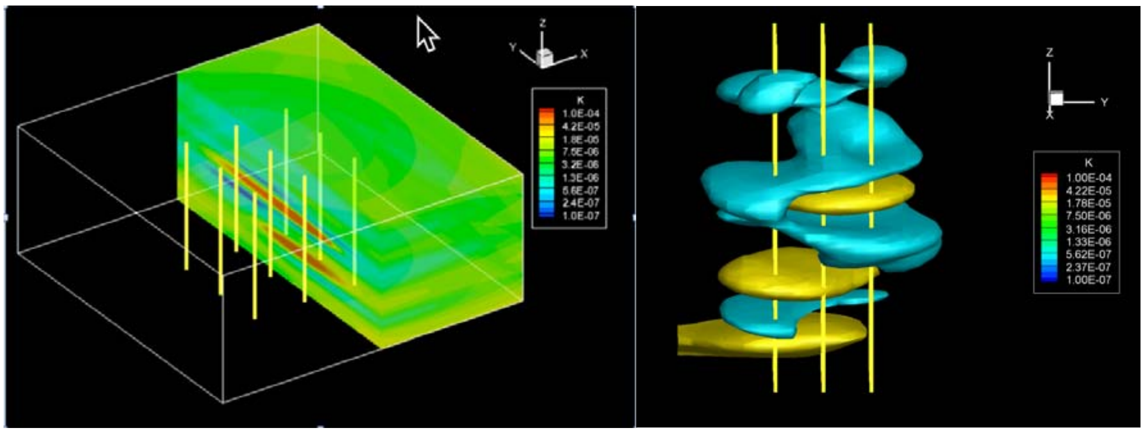

Figure 2-2. 3-D Distribution of K Parameters

Hydraulic stresses are commonly perturbed in an aquifer test by turning extraction and/or injection well(s) on or off to induce propagations of hydraulic head changes at multiple locations throughout the aquifer. If an aquifer interacts with the surface water regime in the vicinity, such as a river, or recharge takes place during rainfall events, hydraulic heads can also be perturbed naturally. Other natural phenomena such as earth tides, barometric pressure fluctuations, and earthquakes, *inter alia,* can also cause hydraulic head variations. However, quantifying the source and its magnitude is critical in utilizing such signals in hydraulic parameter characterization.

At sites where ongoing remedial operations include pump-and-treat systems, HT surveys can be conducted by simply modifying the pumping/injection rates or by taking advantage of the pumping/injection shut-off and commencement operations. Regrettably, these signals are rarely exploited to improve site characterization. Utilizing ongoing pump-and-treat signals to improve site characterization would be attractive to optimizing remediation strategies.

Groundwater flow hydraulic response is dictated by the spatial distribution of the K and S_s parameters. At any location in the aquifer, the K and S_s parameter are uncertain and have infinite number of possible values. In HT, a parameter at a point is treated as a Random Variable (RV). We conceptualize the spatially distributed parameter as a collection of an infinite number of RVs in space, which is referred to as a Random Field (RF). This random field thus has an infinite number of possible spatial distribution patterns. If we also have some samples of K-values at the site (e.g., permeameter analyses of core samples or slug tests), we can further tailor the possible K-fields to the site-specific ones. The RVs at two locations in an aquifer might be correlated. The correlation usually becomes smaller as the separation distance between the two locations increases. A RF model is typically represented in a geostatistical context by: (1) probability distribution to characterize the uncertainty of the RV at a point; and (2) correlation (or variogram) function to characterize the relationship between correlation and separation distance.

A HT analysis typically starts with an initial geostatistical model developed using available geologic information. This geostatistical model is referred to as the prior distribution model in a Bayesian statistical framework. HT analysis updates the statistical model using the data from HT survey in the Bayesian framework. The resulting K-field is called the conditional effective K-field. HT analysis also estimates the uncertainty associated with the estimated K-field. This variance informs us the likelihood that the estimate K-field can deviate from the true K-field.

We adopt a highly parameterized heterogeneous conceptual model, which discretizes the 3-D domain into elements. Our HT analysis utilizes the **Successive Linear Estimator (SLE)** to estimate the most likely K and S_s values (i.e., conditional effective value) for each element, given (conditioned upon) the observed drawdown (or head) data from the HT survey. The SLE is more generalized than the maximum a posteriori (**MAP**) inverse approach and obtains higher-resolution details than the well-known **pilot point** method.

2.1.2 Technology Development Summary

The power of **HT analysis** has been recognized after Yeh and Liu (2000) formally introduced a HT technology that allows the use of sequential pumping tests' data to fully image the 3-D heterogeneity in a synthetic aquifer. Similar to the iterative geostatistical technique developed by Yeh et al. (1996) to successively linearize the nonlinear relationship between hydraulic pressure head and parameters, they developed the Sequential Successive Linear Estimator (**SSLE**) for 3-D steady-state HT (**SSHT**) analysis, which jointly inverts multiple pumping tests to map the K-field and its associated uncertainties. They proved that processing of the data sets from the tomographic survey tests through a consistent mathematical model could yield the detailed spatial distribution of hydraulic properties of the aquifer, patterns of connectivity of highly conductive zones, locations of low conductive zones and the uncertainties associated with the spatial distribution.

Zhu and Yeh (2005) extended the SSLE for transient analysis. Their work showed promising results of utilizing **transient HT** to characterize accurate estimates of both K- and S_s-fields (tomograms). Since then, geostatistics-based inverse methods have been extensively used for HT data interpretation by several research groups.

The first **SSHT in unconfined aquifers** was performed by Cardiff et al. (2009) using nine pumping tests at the Boise Hydrogeophysical Research Site to estimate the distribution of depth-averaged K. Subsequently, Mao et al. (2013) developed **transient HT for unconfined aquifers**, considering the transition of water release mechanics, from aquifer elastic effects to slow drainage of water from unsaturated zone, and from falling of the water table.

The first **large-scale application of 3-D transient HT** in fractured rock was demonstrated by Illman et al. (2009) at the Mizunami Underground Research site in Japan. Using two cross-hole pumping tests, they estimated the 3-D distribution of K and S_s as well as their uncertainties. Zha et al., (2015; 2016) included two more pumping test data sets from both sides of the geologically mapped low permeability fault zone into the SLE analysis. They were able to map the detailed irregular shape of the fault zone and local-scale high-K zones in this large-scale fault zone. Zha et al. (2016) also demonstrated that the estimated K and S_s distribution in this fractured granite site could lead to a satisfactory prediction of flow field of an independent pumping test.

Berg and Illman (2015), through a field investigation, have tried to estimate the K tomograms conditioning on **prior information of aquifer heterogeneity**, such as **permeameter K data**, in order to improve the consistency of K estimates with geological knowledge. Zhao et al. (2016) showed that **geological models** built based on the accurate knowledge of stratigraphy from borehole logs can improve the HT results. Zhao and Illman (2017) clearly demonstrated that prior **information at locations outside** the well field could enhance the estimates of hydraulic properties and predictions of flow, even within the well field at a field site.

Lastly, as advocated by Yeh et al. (2015), even under the ideal case of perfectly known extent and shapes of the geological units, if the hydraulic characteristics of each zone are unknown and the number of observation wells is limited, the zonal hydraulic properties estimated by conventional methods could be erroneous and the prediction could be biased. **A joint inversion of HT, geological, geophysical, and other related information such as groundwater flux, tracer and temperature data can lead to better results and is anticipated to be the future direction of subsurface characterization**.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Compared to the interpretation of borehole cores or cuttings samples, HT is **non-invasive** and more **cost-effective** (especially for deep formations and where direct push approaches have difficulty in high-resolution characterization) for delineating heterogeneous parameter values at all locations. Unlike geophysical tomography, HT **directly** provides an estimation of K- and S_s-values. Prior research has shown that HT data inherently contain more information than single-well pumping tests, and the joint interpretation method is superior to conventional pumping test data analysis methods in delineating the heterogeneities.

A key advantage of the HT technology is the **ability to use existing information and infrastructure** to reduce costs and reduce uncertainty. For sites with existing pump-and-treat systems, historical operational records and water level monitoring data can readily be used in HT analysis. Available information from past site investigations, such as well logs, geophysical survey data, flowmeter profiles, and flux measurements, can be used to reduce the uncertainty of the HT results. Additional HT data collection may not be necessary with respect to the site characterization objectives. If additional HT data is needed, the results from HT analysis using existing data can be used to optimize the data collection efforts and costs. The final results will be consistent with the existing information utilized.

The HT technology directly **delineates the spatial distribution of K- and S_s-fields**, including **both the high-K and low-K zones**. Preferential chemical transport pathways with high K and potential back-diffusion source zones with low K can be identified so that focused remedial actions appropriate for a site can be developed and remediation design can be optimized. Existing remediation systems can be optimized to enhance their performance.

In addition, HT **estimates the uncertainty of the delineated K- and S_s-fields**. Such information can be used to evaluate the reliability of remedial action and to maximize the reliability of remediation design.

A limitation of HT is that the resolution of results is dictated by the density of pumping wells and observation ports in wells. For example, Yeh and Liu (2000) suggested that spacing of the observation ports in observation wells should be about the average thickness of the heterogeneity to be mapped in the vertical direction. Likewise, the spacing in the horizontal direction should be approximately the horizontal extent of the stratification. They also suggested that pumping at four different locations (depths and directions) would be sufficient enough (i.e., the return of extensive pumping diminishes rapidly, although it is still useful).

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3.0 PERFORMANCE OBJECTIVES

The performance of HT in comparison with other conventional site characterization techniques is evaluated using different quantitative and qualitative criteria. These evaluation metrics are summarized in Table 3-1.

Table 3-1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
Determine accuracy of HT against conventional site characterization techniques	Measured drawdown from confirmatory pumping tests; Simulated drawdown by models using K- and S_s-fields estimated by HT and conventional methods.	• Bias (HT) < bias (conventional methods) • Mean square error of drawdown (HT) < Mean square error of drawdown (conventional methods) • Observed drawdown within one standard deviation of simulated drawdown based on uncertainty of K and S_s from HT
Determine uncertainty of HT against conventional site characterization techniques	Variance of K and S_s estimated by HT and conventional methods	Variance (HT) < variance (conventional methods)
Qualitative Performance Objectives		
Determine consistency of HT results with geologic/lithologic data	K- and S_s-fields estimated by HT; lithologic/geologic data	Spatial distribution of K and S_s from HT is superior to interpretation from geologic/lithologic data at pumping and observation wells
Determine cost-effectiveness of HT against conventional techniques	Cost for implementing HT and conventional techniques	HT is more cost-effective than conventional techniques
Determine the ease of use for HT against conventional techniques	Level of expertise needed to implement HT and conventional techniques	HT does not require higher level of expertise for implementation in comparison to conventional techniques
Determine the capability of identifying potential low permeability zones	Inferred low-permeability zones from HT and conventional techniques	HT did not miss the low-permeability zones inferred from conventional techniques using data from pumping and observation wells

4.0 SITE DESCRIPTION

4.1 SITE LOCATION

The **NCRS** is located on the UW campus in Waterloo, which is approximately 100 kilometers west of Toronto, Ontario, Canada. (Figure 4-1).

Figure 4-1. UW NCRS Location ¶red solid star) (from Google Maps).

The **AFP44 site** is a Superfund site located in the southern portion of the Tucson International Airport Area (TIAA) Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) site, approximately eight miles south of downtown Tucson, Arizona. Figure 4-2 shows a map of the area indicating the location of the 1266-acre AFP44 site. A brief history of the site and a chronology of events can be found on the Arizona Department of Environmental Quality (ADEQ)'s website.

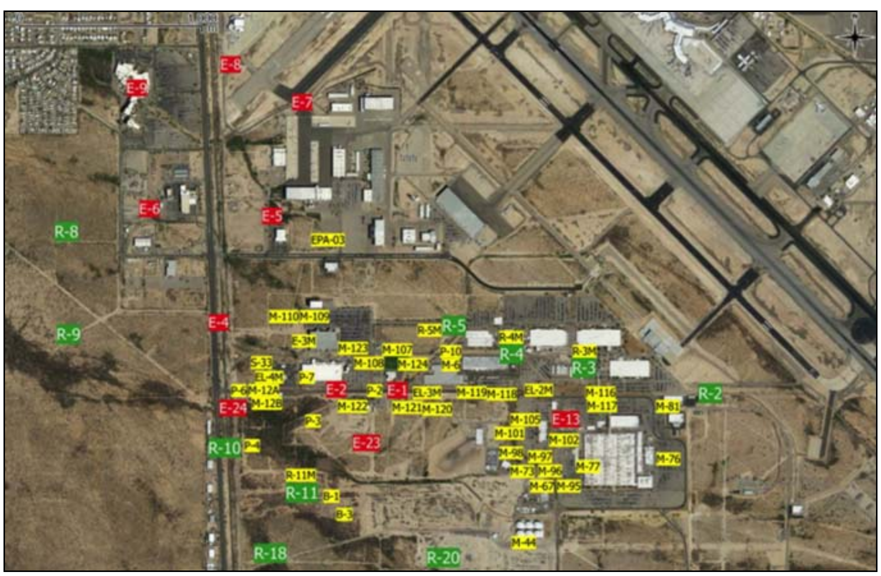

Figure 4-2. Map of AFP44 Site in Tucson, Arizona

4.2 SITE GEOLOGY/HYDROGEOLOGY

The **NCRS** is located within the Waterloo Moraine, which is a highly heterogeneous interlobate feature composing of kettle and kame deposits that contain alternating layers of till and glaciofluvial material (Figure 4-3). The main feature of the site is an "aquifer zone" located approximately 8 to 13 meters (m) below ground surface (bgs). This zone consists of **two high K units that are separated by a discontinuous low K layer**. The upper aquifer is composed of sand to sandy silt, and the lower aquifer is composed of sandy gravel. Near the ground surface, the aquifer system is generally **confined** by a laterally extensive upper aquitard layer. The **low K aquitard** units separating the two aquifers and near the surface is known to contain **stratigraphic windows** in some areas and is known to provide hydraulic connection based on previous pumping tests (Alexander et al., 2011). None of the units extend across the entire study site. Situated above and below the aquifer zone are low K silts and clays. At approximately 18 m bgs is the dense Catfish Creek Till, which acts as a hydraulic barrier (Alexander et al., 2011) and is taken to represent the bottom boundary for this study. Water levels collected in the vicinity of the site indicate that groundwater flow is toward the southeast. Depth to water is relatively shallow.

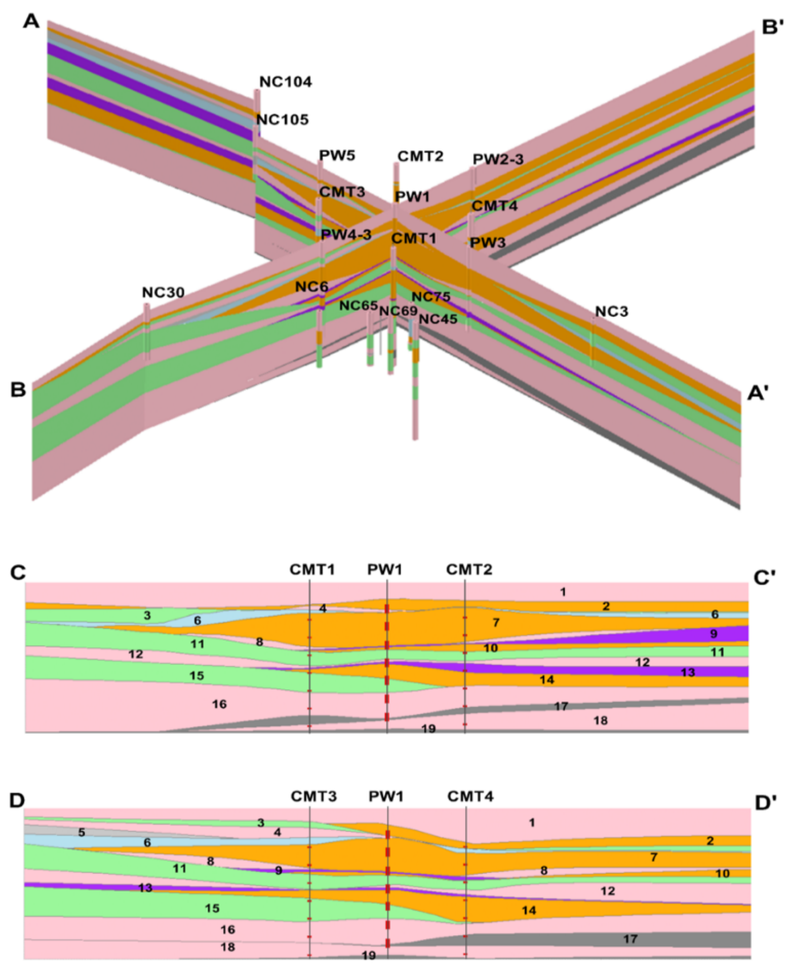

Figure 4-3. Stratigraphic Model of the NCRS

Numbers in cross section C-C' and D-D' indicate the 19 layers of different materials: Clay (1, 4, 8, 12, 16, 18); Silt and Clay (17, 19); Silt (2, 7, 10, 14); Sandy Silt (6, 9, 13); Sand and Silt (5); Sand (3, 11); Sand and Gravel (15). Screened locations are shown on wells depicted in cross sections C-C' and D-D'.

The **AFP44 site** is situated on the western edge of the Tucson Basin, within the intersection of the large, ancient Cienega Alluvial fan and the Santa Cruz River, both of which are highly heterogeneous systems in a complex and unpredictable depositional environment. Average annual precipitation was 11.59 inches between 1981 and 2010. The regional groundwater flow direction is to the northwest. Groundwater at the site is hydraulically controlled by an active remediation system that extracts, treats, and then re-injects the treated water on site. For the past 13 years, the water table at the AFP44 site has risen 80 feet in response to the Pima Mine Road Recharge Project due to the proximity (5 miles) of the AFP44 site to the infiltration ponds.

Figure 4-4 shows a 3-D view of the subsurface conditions at AFP44. The study area is underlain by at least 600 feet of unconsolidated to semi-consolidated alluvial sediments characterized into three primary stratigraphic units: Holocene Alluvium (a few feet to approximately 30 feet bgs), Fort Lowell Formation (depths down to 220 feet bgs), and Tinaja beds (below the Fort Lowell Formation to 600 feet). There are two aquifer zones identified within these basin-filled sediments, labeled as the semi-confined **Upper Zone (UZ)** within the Fort Lowell Formation and the confined water production **Lower Zone (LZ)** (Figure 4-5). The UZ is the most permeable aquifer unit.

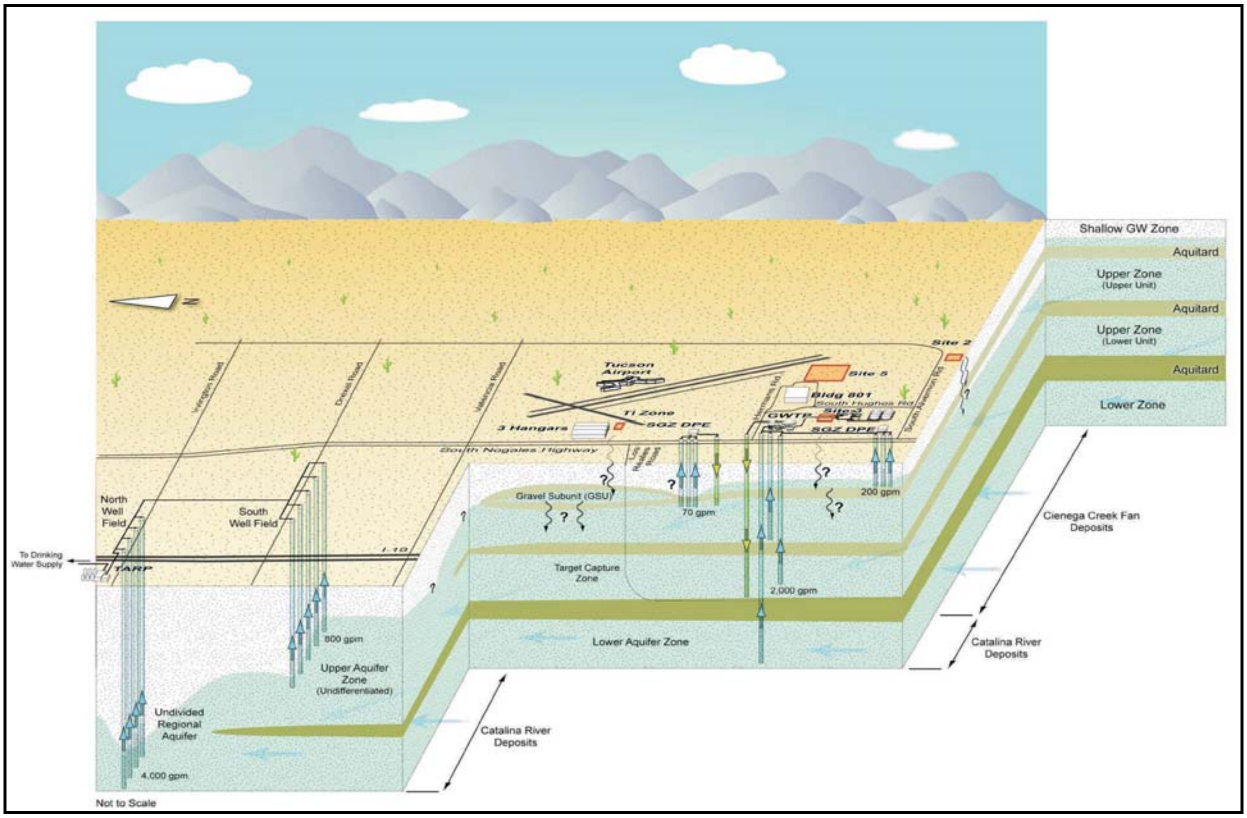

Figure 4-4. 3-D perspective View of the Subsurface Conditions at AFP44

(source: AECOM)

The UZ, containing most of the contaminants, is the focus of the AFP44 groundwater remediation project. Based on data from extraction and recharge wells onsite, the estimated average K ranges from 13 feet/day to 133 feet/day. The UZ extends to 220 feet bgs and is further subdivided into two aquifer subunits, the **UZ Upper Unit (UZUU)** ranging from the water table to 160 feet bgs, and the **UZ Lower Unit (UZLU)** from 160 to 220 feet bgs. The two units are separated by an aquitard that is present over much of the study area that pinches out to the west where the UZ is possibly undivided. Where present, the confining unit is typically 55 feet thick, hydraulically isolating the UZUU and UZLU. The UZLU is lithologically similar to UZUU, but it contains a higher percentage of gravel. Most of the extraction wells at AFP44 are screened across both the UZUU and UZLU. However, a larger portion of the pumped water comes from the UZLU. Hydraulic heads are typically lower in the UZLU than in the UZUU. The hydraulic connection between the different aquifer zones is believed to be minimal due to orders of magnitude differences in the estimated K between zones separated by relatively thick confining units.

The LZ is separated from the UZ by a confining unit correlated with the Upper Tinaja beds that is comprised of a clayey silt and mudstone from the base of the UZ to about 250 to 300 feet bgs. This confining unit pinches out to the west and north of the project area, creating an undivided regional aquifer. The LZ has a lower average estimated K of 0.1 to 1.3 feet/day, attributed to less coarse-grained sediments and more consolidation and cementation than in the UZ. The vertical hydraulic gradient between the UZ and the LZ is downward.

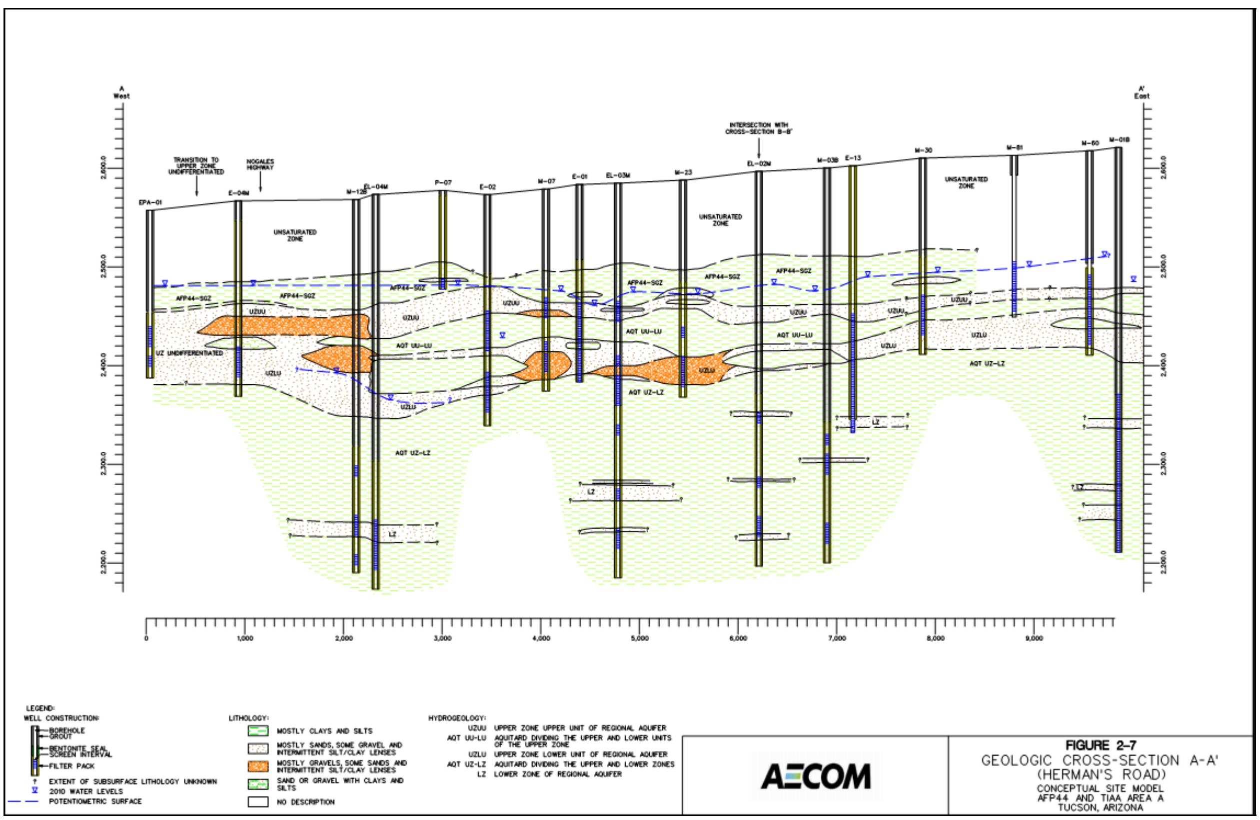

Figure 4-5. Stratigraphic Model of AFP44 Site

(from AECOM, 2012)

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5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The HT pumping tests were designed to perturb the hydraulic head fields spatially and to measure the hydraulic responses at multiple locations to each perturbation. These tests were performed **using the existing well networks and site facilities at both the NCRS and AFP 44 sites**. At the NCRS, pumping tests were designed to extract (or inject) groundwater from (or to) individual screen intervals to generate hydraulic stresses at distinct locations. At the AFP44 site, pumping tests were designed to modify the pumping rates at the extraction and injection wells to generate changes in the spatial distribution of hydraulic stresses. The total extraction rate and total injection rate need to be maintained within a minimum flow rate of 2,500 gallons per minute (gpm) and a maximum flow rate of 5,000 gpm, as required by the onsite treatment system.

Two sets of HT pumping test data were collected at each site. Pressure transducers were installed in the monitoring wells to collect hydraulic response data during the HT pumping tests. These transducers also recorded data before and after the pumping tests to provide data for removal of background trends in the data. One set was used in the HT analysis to **delineate the K and S_s distributions.** The resulting K and S_s distributions are used to predict the second set of pumping test data. A comparison of the predicted and observed pumping test responses for the second dataset was used to **evaluate the performance of HT**. In addition, the delineated K and S_s distributions were compared with existing lithologic information and permeameter test results.

5.2 BASELINE CHARACTERIZATION

At the **NCRS**, Alexander (2009) and Alexander et al. (2011) analyzed five continuous soil cores collected during the installation of pumping and monitoring wells. K values were estimated from 471 permeameter analyses of core samples and 270 grain size distribution data. Drawdown data from several pumping tests indicate that the permeable unit behaves as a semi-confined aquifer. K values were estimated from the pumping tests and 28 slug test data using analytical solutions based on the assumption of uniform medium. Based on raw permeameter K values, Alexander et al. (2011) estimated the $\sigma^2_{\ln K}$ to be 6.5. The estimated vertical correlation length for the site was approximately 15 centimeters, and K was found to vary over five orders of magnitude.

The available **AFP44 site** information is from the preliminary site investigation work completed by the AFP44 consultants. The baseline characterization activities include groundwater level measurements at all observation wells. Groundwater levels at all the wells was conducted prior to the initiation of a HT survey. A network of pressure transducers was installed. The pumping rates at extraction and injection wells, and selected observation wells were monitored.

5.3 FIELD TESTING

The **NCRS** is instrumented with a total of seven wells (PW1, PW3, PW5, CMT1, CMT2, CMT3, and CMT4) and two well nests (PW2 and PW4) in a 15 m × 15 m area (Figure 5-1). Continuous multichannel tubing (CMT) wells, containing seven channels each (seven screened intervals), are used strictly as observation wells and are installed in between the four corners of the square pattern. The remaining five wells are pumping wells (PW), three of which are multiscreen wells (PW1 contains eight screens, PW3 and PW5 contains five screens).

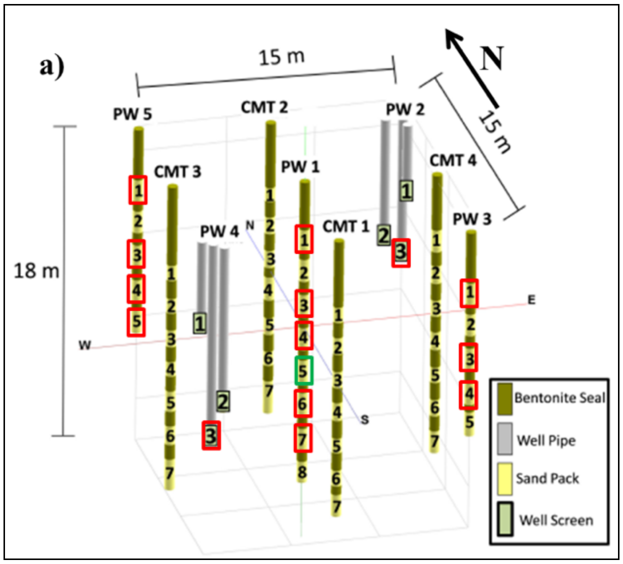

Figure 5-1. 3-D perspective View of Various Wells and Pumping Locations

Table 5-1. Summary of Pumping/Injection Tests Performed at NCRS

Well Location	Pumping Rate (Liters/minute)	Duration (hour)	Type
PW1-1	1.89	4.5	Injection
PW1-3	10.50	6	Pumping
PW1-4	6.30	8.5	Pumping
PW1-5	4.40	22.5	Pumping
PW1-6	0.95	6.5	Pumping
PW1-7	1.05	26.5	Pumping
PW2-3	1.91	7	Pumping
PW3-1	0.94	4.4	Injection
PW3–3	2.10	22	Pumping
PW3–4	1.50	22	Pumping
PW4–3	30.20	22.5	Pumping
PW5-1	0.85	4.52	Injection
PW5–3	7.80	22	Pumping
PW5–4	7.80	8.5	Pumping
PW5–5	8.10	22	Pumping

A total of 15 pumping and injection tests obtained through this study, along with the Berg and Illman (2011) data have been conducted at the NCRS (Table 5-1). These tests ranged in duration from 4.4 hours to 26.5 hours. A pressure transducer network was installed to collect pressure head data at up to 44 observation ports. For the multi-screen wells (PW1, PW3, or PW5), FLUTe (*FLUTe Ltd.*) liners were installed in the well not used for pumping to prevent hydraulic short circuiting between adjacent screens within the well.

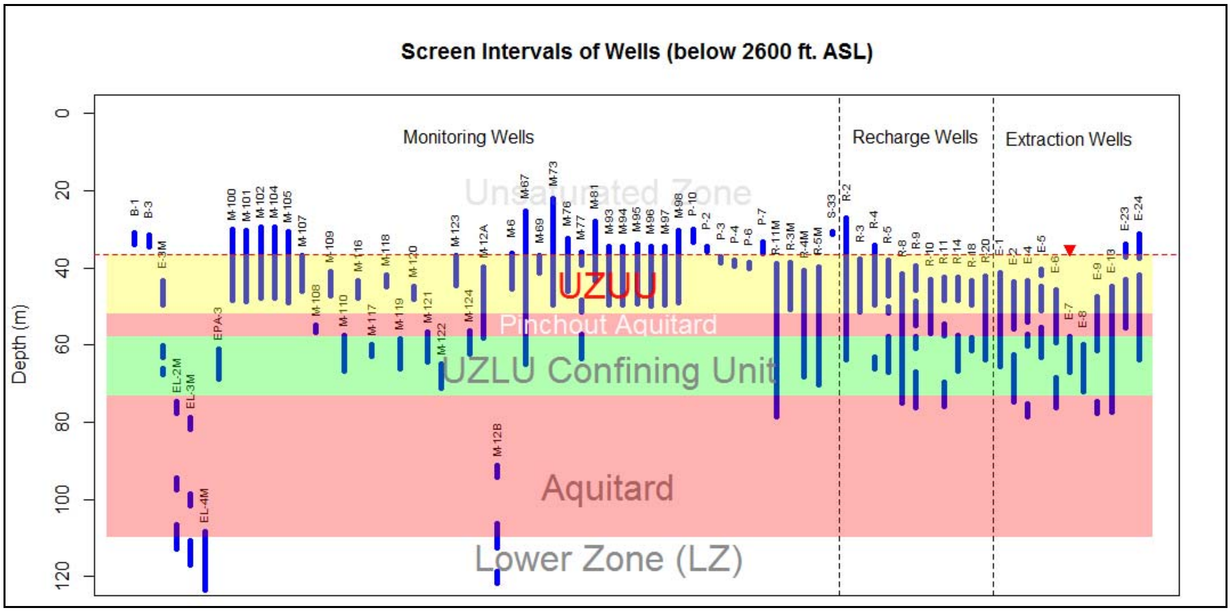

Figure 5-2. Screen Intervals of Wells

An active groundwater remediation system has been operating at the **AFP44 site**. The system is composed of numerous wells for extraction (including dual phase extraction), injection, and monitoring. The demonstration is in an approximately 4.6 square-mile area. Figure 4-2 shows the extraction wells, injection wells, and monitoring wells available for this study. Most of the extraction wells and observation wells are completed within the UZ of the regional groundwater zone (Figure 5-2). From June of 2014 to August of 2015, 44 pressure transducers were installed in selected monitoring wells.

The water levels at the wells were continuously monitored and were recorded at two-minute intervals. The recorded groundwater levels were confirmed by independent measurements using a water level sounder. Transducer data were downloaded and the transducers were reprogrammed periodically. Daily average pumping rates at extraction wells and injection wells were recorded. From the various recorded events, we chose four for the HT interpretation and analysis: 1) rate change at E-13 in July 2014; 2) the shutdown of E-23 in November 2014; 3) the system shutdown in April 2015; and 4) the rate change at E-24 in May 2015. For validation of the K- and S_s-field generated by HT, the data from the system shutdown in January 2015 were used.

5.4 DATA ANALYSIS AND RESULTS

5.4.1 NCRS at UW, Canada

The NCRS data selected for this study includes potentiometric head responses recorded between 1 and 1,600 minutes after commencing. One to three points were selected to define each curve. Data showing negligible responses were also included in the HT analysis as they provide lack-of-hydraulic-connection information between the pumped and observation ports. Seven pumping tests (PW1-1, PW1-4, PW1-6, PW2-3, PW3-3, PW4-3, and PW5-3) are used for calibration, while the other seven pumping tests (PW1-3, PW1-5, PW1-7, PW3-1, PW3-4, and PW5-5) are selected for model validation. A 70 m × 70 m × 17 m domain, extending beyond the wells, was discretized into elements with sizes decreasing from 5 m × 5 m × 0.5 m at the boundaries to 0.5 m × 0.5 m × 0.5 m in the well area. The top and bottom faces are defined as no-flow boundaries, while the other four faces are kept as constant head boundaries.

Three different parameterization cases referred to as Case 1 through Case 3, each including subcases, were considered for inverting the HT data in this study. A comparison of simulated and observed drawdown from model calibration is shown in Figure 5-3. The estimated K-distribution is shown in Figure 5-4. Figure 5-5 shows the residual variance of the estimated K-distribution.

Case 1: Effective Parameter Approach

We considered two subcases: (1) isotropic aquifer (**Case 1a**) and (2) anisotropic aquifer (**Case 1b**). The calibration of Case 1a yielded an estimated effective parameter, K_{eff}, of 8.4×10^{-6} meters per second (m/s), with upper and lower limits between 9.8×10^{-6} m/s and 7.2×10^{-6} m/s. For the anisotropic Case 1b, the anisotropic effective parameters, K_x, was estimated as 1.04×10^{-5} m/s with an upper limit of 1.54×10^{-5} m/s and a lower limit of 7.02×10^{-6} m/s; K_y was estimated as 1.19×10^{-5} m/s with an upper limit of 1.68×10^{-5} m/s and a lower limit of 8.36×10^{-6} m/s; and K_z was estimated as 6.37×10^{-7} m/s with an upper limit of 1.08×10^{-6} m/s and a lower limit of 3.75×10^{-7} m/s.

Case 2: Geological Zonation Approach

We considered two subcases: (1) 5-layer (**Case 2a**) model and (2) 19-layer (**Case 2b**) model. Generally, the calibration of the 5-layer geological model yielded the highest K value for the sand and gravel layer (layer 15) and the lowest K value for the bottom merged layer 16^*, consisting of silt and clay layers (layer 16 through 19) (Figure 4-3). K estimates for merged layer 1^* and 12^* are close to the initial value of 8.0×10^{-6} m/s. The estimated K values for layers 3 and 5 have significantly large 95% confidence intervals comparing to those of the other layers. One reason is that layers 3 and 5 only exist in a narrow portion of the geology model and also are far from the pumping and observation wells, thus very few, or no observation data are available in these layers. K estimates for the main sand layers of the 19-layer model show some similarities to the 5-layer geological model, by estimating a relatively high K value for Layer 15, while estimating a low K value for Layer 11. More details about the interlayering of high and low permeability zones are revealed in Case 2b for the upper part of the domain than in Case 2a (Figures 5-4a and 5-4b).

Case 3: Geostatistical Inversion Approach

We considered four subcases of different prior distributions. The K-field correlation scales of the prior distributions for all subcases are set as $\lambda_x = \lambda_y = 4$ m, and $\lambda_z = 0.5$ m, and a variance is set to be $\sigma_{\ln K}^2 = 5$. In **Case 3a**, the inversion starts with a uniform mean field of $K = 8.0 \times 10^{-6}$ m/s, which is the same as the initial K value used in the effective parameter and geological zonation approaches. For the other three cases (Cases 3b – 3d), geologic information is used as prior knowledge for the inversion. Specifically, **Case 3b** used the estimated K values from Case 2a as the prior mean distribution; **Case 3c** used the K estimates from Case 2b as the prior mean distribution; **Case 3d** used the 19-layer geological model (Case 2b) populated with permeameter tested K values as the prior mean distribution.

Results obtained from calibrating Cases 3b, 3c and 3d suggested that when geologically distributed K-fields are used as prior distributions, HT analysis using geostatistical inversion approach could yield K tomograms consistent with geological features. This would be helpful for HT to correctly capture the stratigraphic features for areas where only limited pressure head data are available.

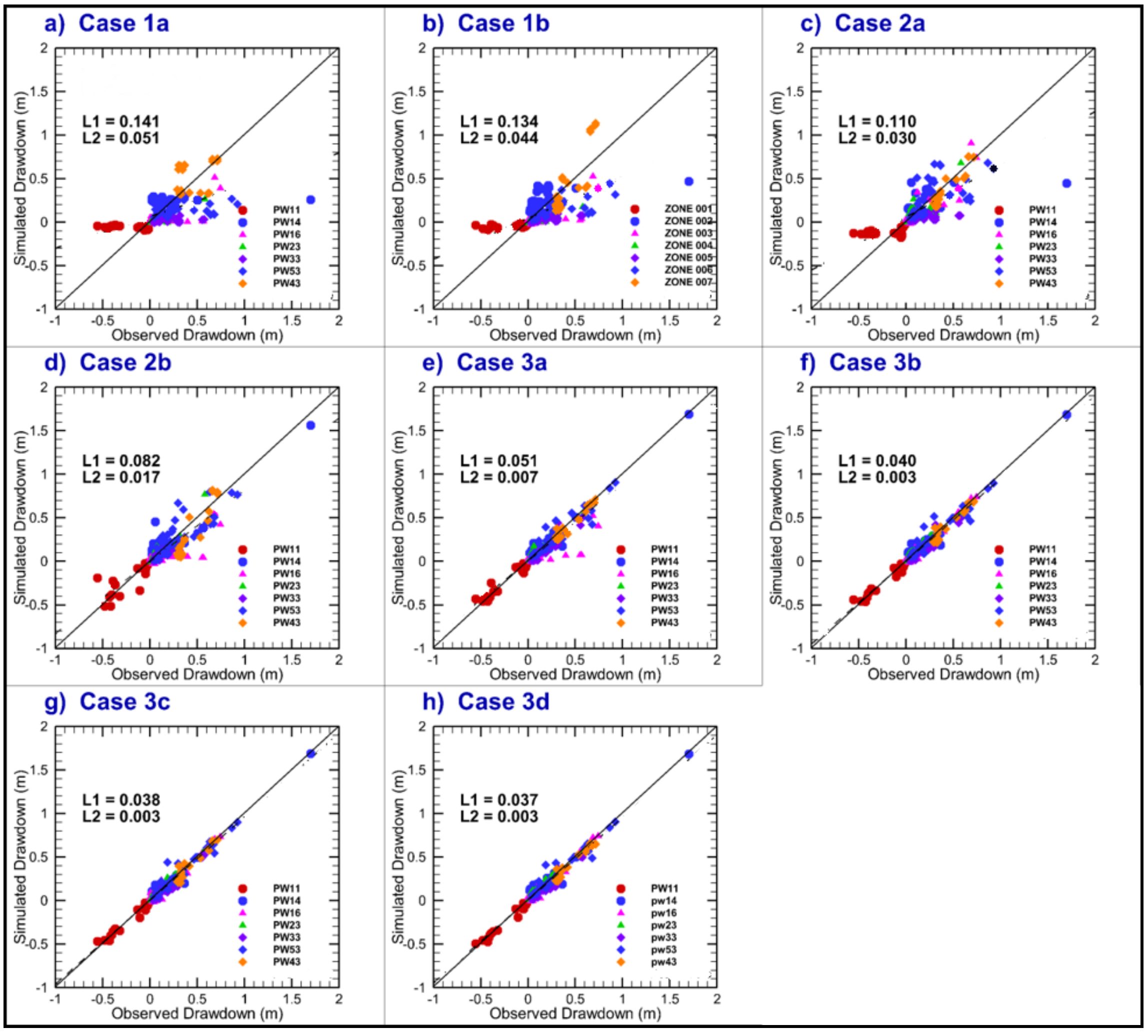

Figure 5-3. Scatterplots of Observed Versus Simulated Drawdowns for Model Calibrations Using Seven Pumping Tests

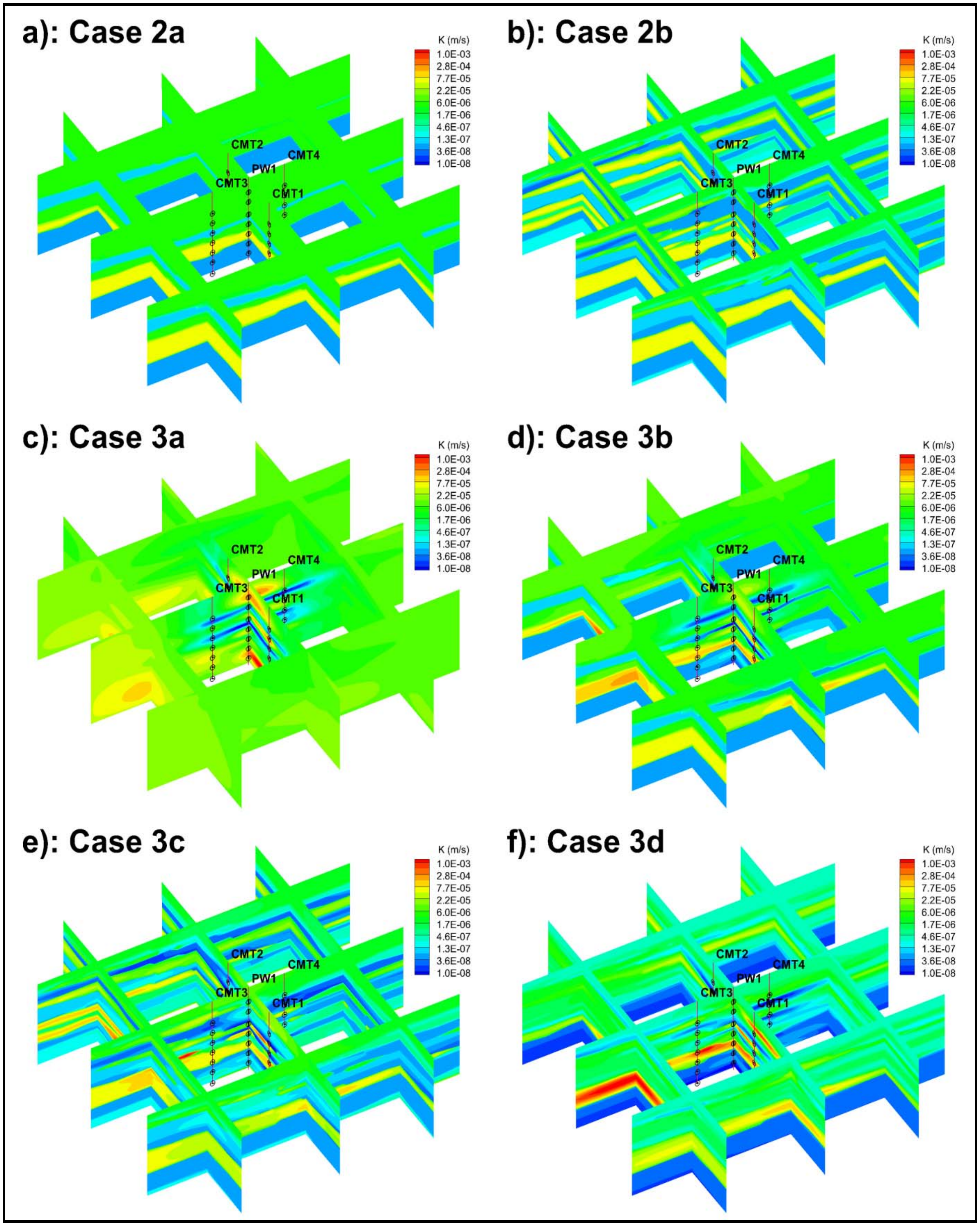

Figure 5-4. **Estimated K-fields from the Inversion of Seven Pumping Tests**

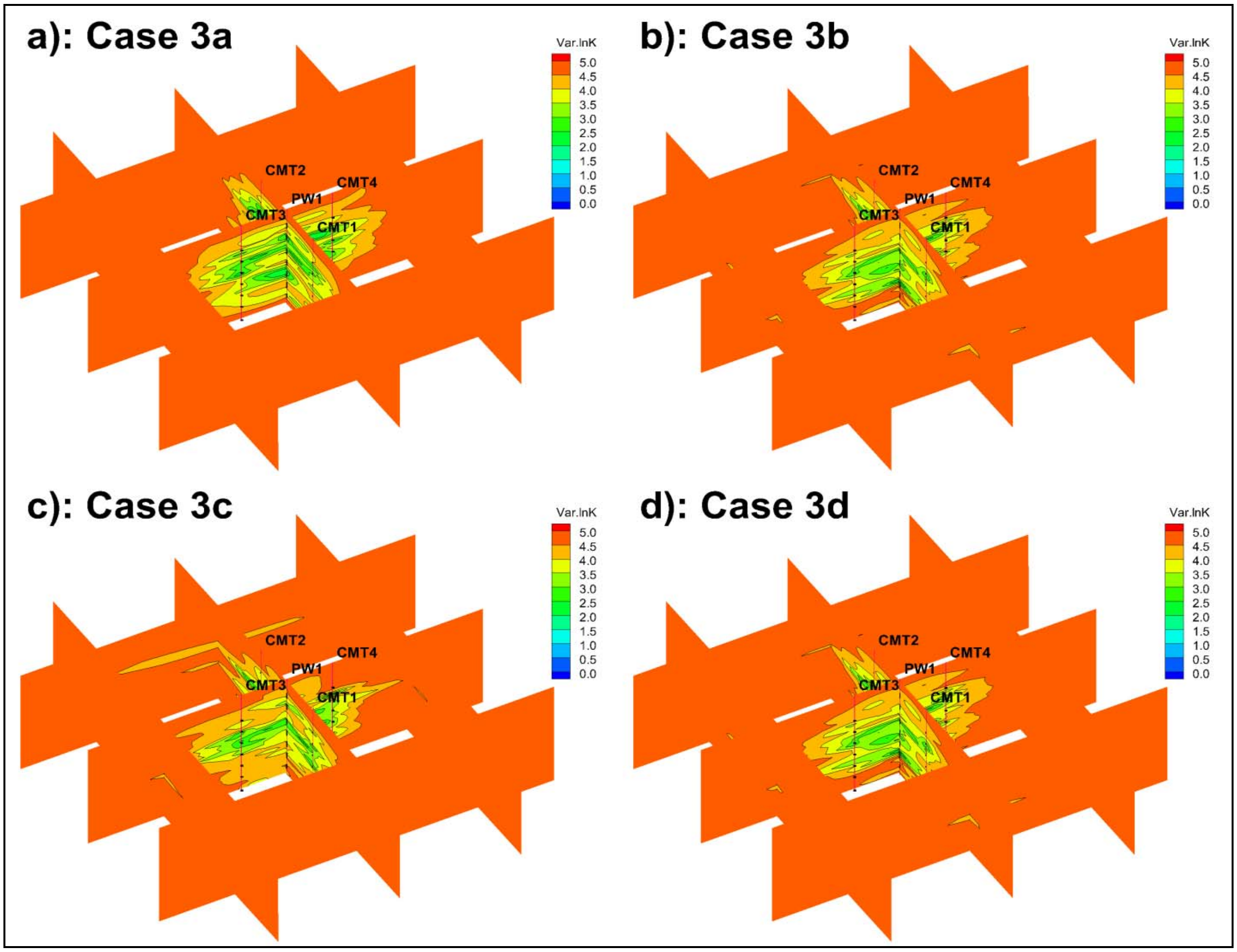

Figure 5-5. Residual Variances of Estimated lnK-fields from the Model Calibration

5.4.2 AFP44 Site in Tucson, Arizona

Examination of pumping and injection record indicates that there are three main types of events contributing to head changes: (1) system shutdown and resume; (2) changes in pumping and injection strategy; and (3) fluctuation of flow rates. The injection records appear to be quite smooth. We have observed and recorded 10 system shutdown events as well as several notable shutdown and recovery events of individual wells. Since we have little knowledge about flow rate changes within the day, we assumed average flow rate.

Head records from observation wells reveal significant layering at the site. Heads in wells screened in the Shallow Groundwater Zone and LZ do not change with time, indicating they do not respond to changes in pumping or injection in UZ. Some UZUU and UZLU pairing wells at the same horizontal location show different responses, indicating the separating aquitard is an effective flow barrier. Observation wells screened across UZUU are more responsive to injection changes, while those screened across UZLU are more responsive to pumping changes, as most injection wells are screened across UZUU and most pumping wells are screened across UZLU.

We first built a simplified two-dimensional (2-D) model with an aquifer thickness of 60 m to investigate the influence of well settings and initial prior information. The 4,000 m x 3,000 m domain is discretized into 50 m x 50 m elements. Figure 5-6 shows the estimated K- and S_s-fields. Figure 5-7 shows the estimated residual variance of the K- and S_s-fields. The residual variance values were decreased by more than 80% (i.e., uncertainty reduced) at some locations where the observation wells are clustered or in locations near the pumping or injection wells.

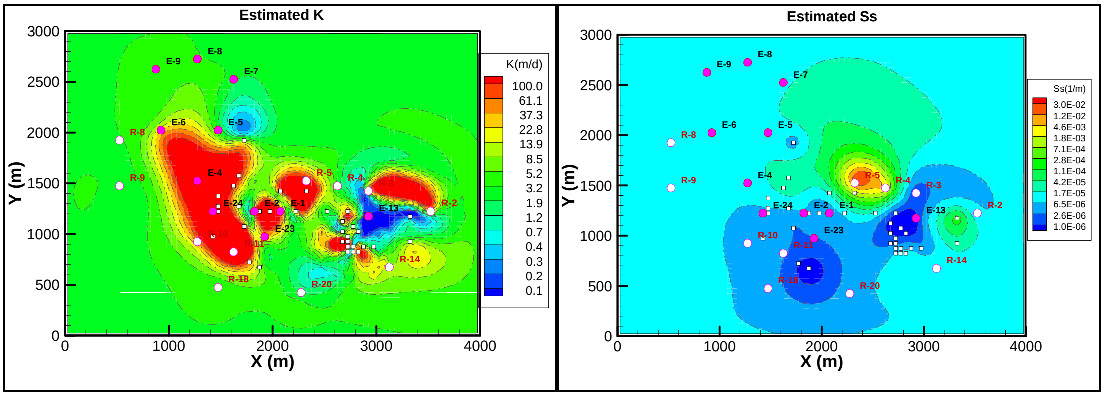

Figure 5-6. Estimated K and S_s Fields Used in the 2-D Case

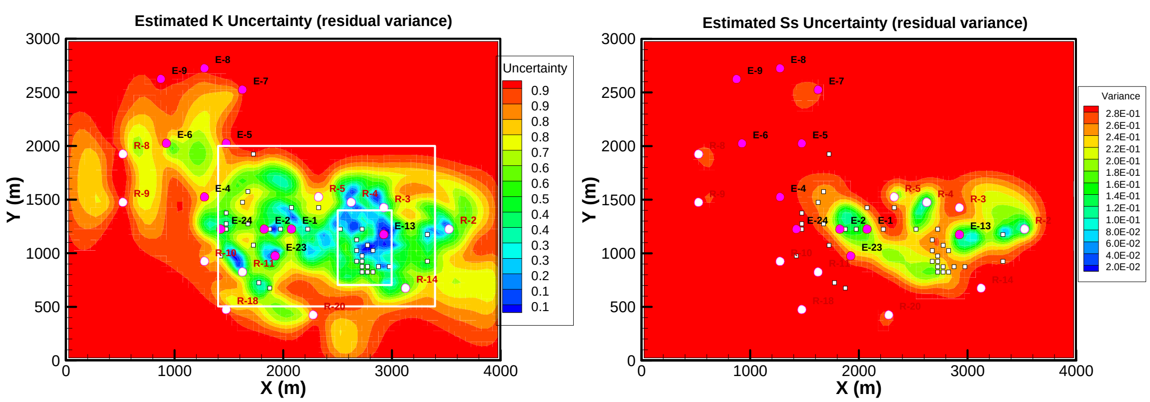

Figure 5-7. The Uncertainty (residual variance) of Estimated lnK and lnS_s in 2-D Case

After the 2-D HT analysis, we performed 3-D HT inversion using a 20-layer model vertically discretized from the 2-D model and accounting for long well screen intervals. A conventional MODFLOW model was created and calibrated for comparison with the HT model. The estimated K distribution exhibits a low K zone (Figures 5-8 and 5-9) in the southeast region, which is consistent with the 2-D results. 3-D HT results are noticeably better than those in the 2-D case. This indicates that the 3-D conceptual model is more realistic for the characterization of the flow and heterogeneity at this site. The results show strong vertical heterogeneity. It should be noted that the figures showing the estimates have different scales for vertical and horizontal directions.

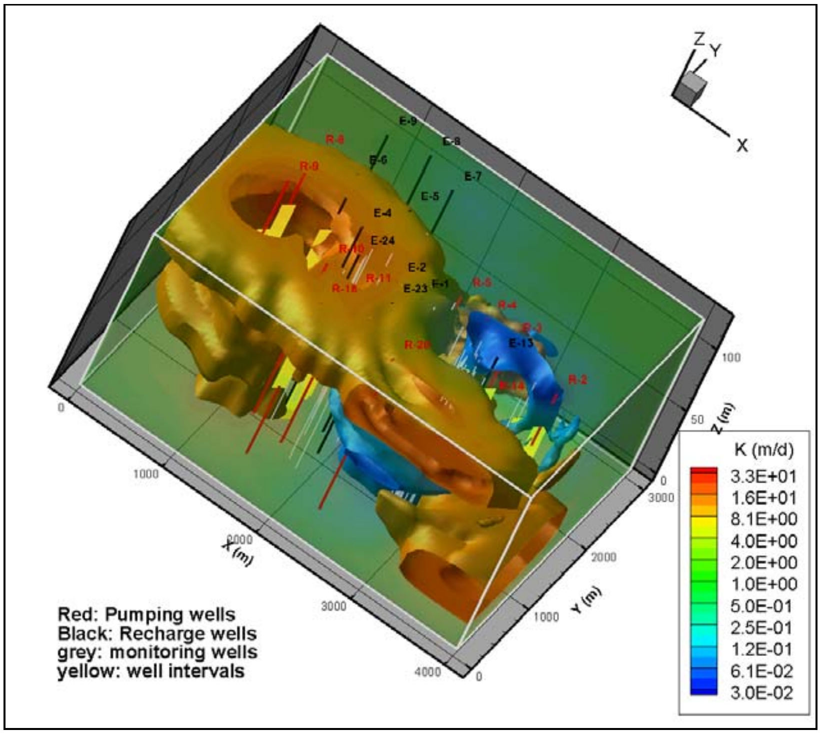

Figure 5-8. Isosurfaces of the Estimated High K and Low K Zones Using a 3-D Model

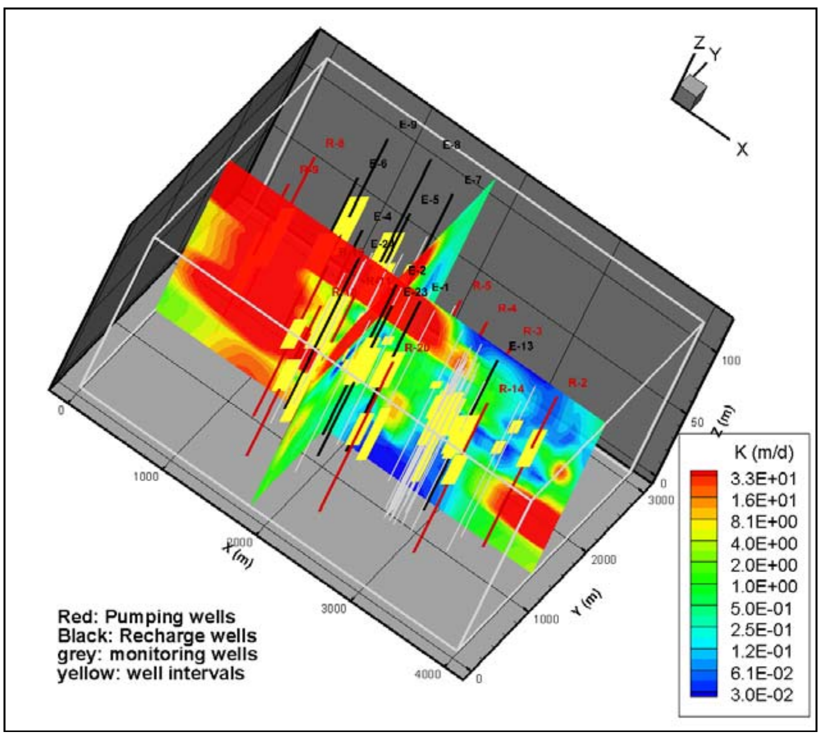

Figure 5-9. Slices of the Estimated High K and Low K Zones Using a 3-D Model

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6.0 PERFORMANCE ASSESSMENT

6.1 PERFORMANCE OBJECTIVE: DEMONSTRATE HIGHER ACCURACY OF HT AGAINST CONVENTIONAL SITE CHARACTERIZATION TECHNIQUES

The effectiveness of site characterization methods is measured by the extent to which the observed pumping test responses match the predictions based on the estimated hydrogeologic parameters. The results from the demonstrations at both the AFP44 and NCRS sites demonstration **confirmed that the HT is more accurate than conventional site characterization techniques.**

6.1.1 NCRS at UW, Canada

The scatterplots of observed and simulated drawdowns are shown in Figure 6-1. Figures 6-1(a) to 6-1(h) revealed that the results of drawdown predictions improve gradually from the effective parameter approach (Case 1) to the highly parameterized approach based on HT inversion (Case 3). The HT Case 3d, using the uncalibrated **geological model populated with permeameter K data as a prior distribution, performed the best**. When geologically distributed K values were used as prior distributions, it is interesting to note that the geostatistical inversion Cases 3b, 3c and 3d performed quite closely in terms of model calibration and validation.

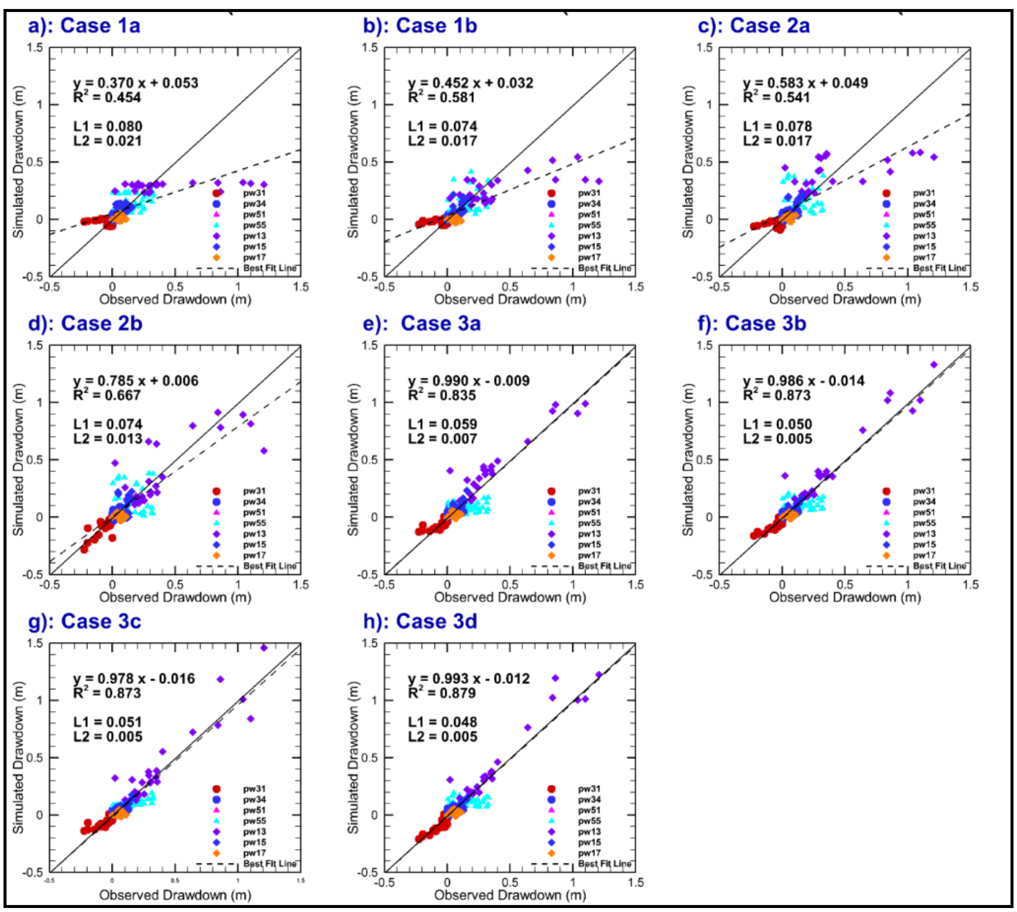
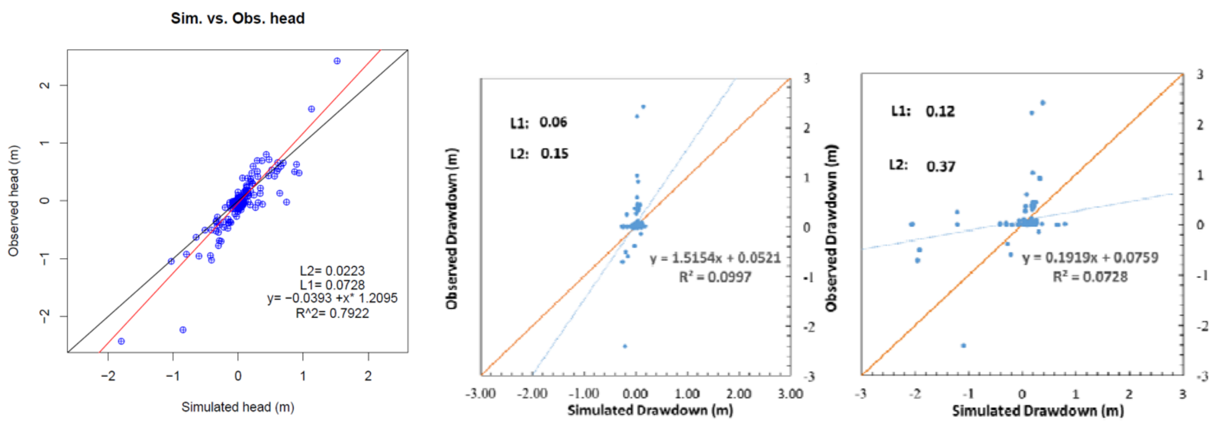


Figure 6-1. Scatterplots of Observed Versus Simulated Drawdowns for Model Validation Using Seven Pumping Tests

6.1.2 AFP44 Site in Tucson, Arizona

Figure 6-2 shows a similar plot for the AFP44 validation test. The HT model results are shown in Figure 6-2(a). The homogeneous and layered model results are shown in Figure 6-2(b) and (c). The mean square error (uncertainty) of the HT result is persistently smaller. The figure **clearly shows that the HT predictions outperform the predictions from conventional models**.



(a) HT model **(b) Homogeneous model** **(c) Layered model**

Figure 6-2. Simulated Versus Observed Drawdown of AFP44 for Validation Pump Test

6.2 PERFORMANCE OBJECTIVE: DEMONSTRATE LOWER UNCERTAINTY OF HT AGAINST CONVENTIONAL SITE CHARACTERIZATION TECHNIQUES

Estimation variance of K- and S_s-values is a measure of the uncertainty associated with estimation methods. The results from the demonstrations at both the AFP44 and NCRS sites **confirmed that the HT results are less uncertain than the results from conventional site characterization techniques**.

6.2.1 NCRS at UW, Canada

For NCRS, the smallest parameter variance of both the homogeneous and layer model is 1.00 for K in natural scale. Converting the highest single-element variance obtained by HT (Figure 5-5) into a uniform variance over one layer gives 0.33 for K, which is already lower than the uniform average over a set of layers, let alone over the whole model.

6.2.2 AFP44 Site in Tucson, Arizona

The variance of K and S_s in the homogeneous model are 1.02 for K and 2.13 for S_s in the natural scale. In the layer model, the smallest variances for K and S_s are 1.10 and 1.05, respectively. Figure 5-7 shows the variance of the K- and S_s field estimated by HT. Converting the highest single-element variance into a uniform ensemble variance over one layer are much lower than the smallest variances for K and S_s for the layer model.

6.3 PERFORMANCE OBJECTIVE: ILLUSTRATE CONSISTENCY OF HT RESULTS WITH LITHOLOGIC/GEOLOGIC DATA

The consistency of the K-field delineated by HT with available core information is a qualitative indication of the accuracy of HT. The results from the demonstrations at both the NCRS and AFP44 sites **confirmed the consistency of HT results with the current spatial distribution knowledge of the more permeable and less permeable regions.**

6.3.1 NCRS at UW, Canada

We compared the estimated K values of all scenarios from Cases 2 and 3 to permeameter K values obtained along the CMT wells to examine the intra- and inter- layer K variations among different subsurface characterization approaches (Figure 6-3). Case 3a results reveal that when a homogeneous K-field is used as the prior mean, the geostatistical inversion approach has only captured the general features of high and low permeable layers within the range of 5 m to 12 m, and K estimates for the area away from the well field are relatively smooth due to lack of observation data. However, when geologically distributed K-fields are used as prior distributions (Case 3b, Case 3c and Case 3d), the fits between the estimated and permeameter tested K values for all CMT wells are consistently improved. The improvements are most obvious for the high K zone located between 4 m and 7 m above the bottom of the modeling domain, as well as the low K zone near the bottom domain. Additionally, the fit of K profiles in Case 3b with a 5-layer geological model used as a prior distribution in the geostatistical inversion approach is comparable to those from Cases 3c and 3d, in which a 19-layer geological model is used. This finding indicates that **a simple geological model reflecting the general geological structure may be sufficient for use as a prior distribution** in geostatistical inversion approaches to characterize heterogeneity within the area of interest. Another important feature of the estimated K tomogram of Case 3a is the incorrect mapping of the clay zone at the bottom of the simulation domain. We find that the use of transient information correctly resolves the bottom low K zone with pumping test data alone. Overall, the above comparisons suggest that the use of geological data is helpful for the geostatistical inversion approach for HT investigations in preserving structural features of the hydraulic property field. By contrast, the K profiles obtained from both calibrated conventional models showed some inconsistency to permeameter-tested results along nine wells. Such inconsistency could be attributed, on the one hand, to using geological zonation with each layer as homogeneous, and on the other hand, to the compensation effect of parameter values to structural errors. We plotted K estimates for Case 3d models (Figure 6-4) along cross section D-D’ (Figure 4-3) for a detailed comparison to the geologic model cross-section. The location of this cross-section is shown in Figure 4-3.

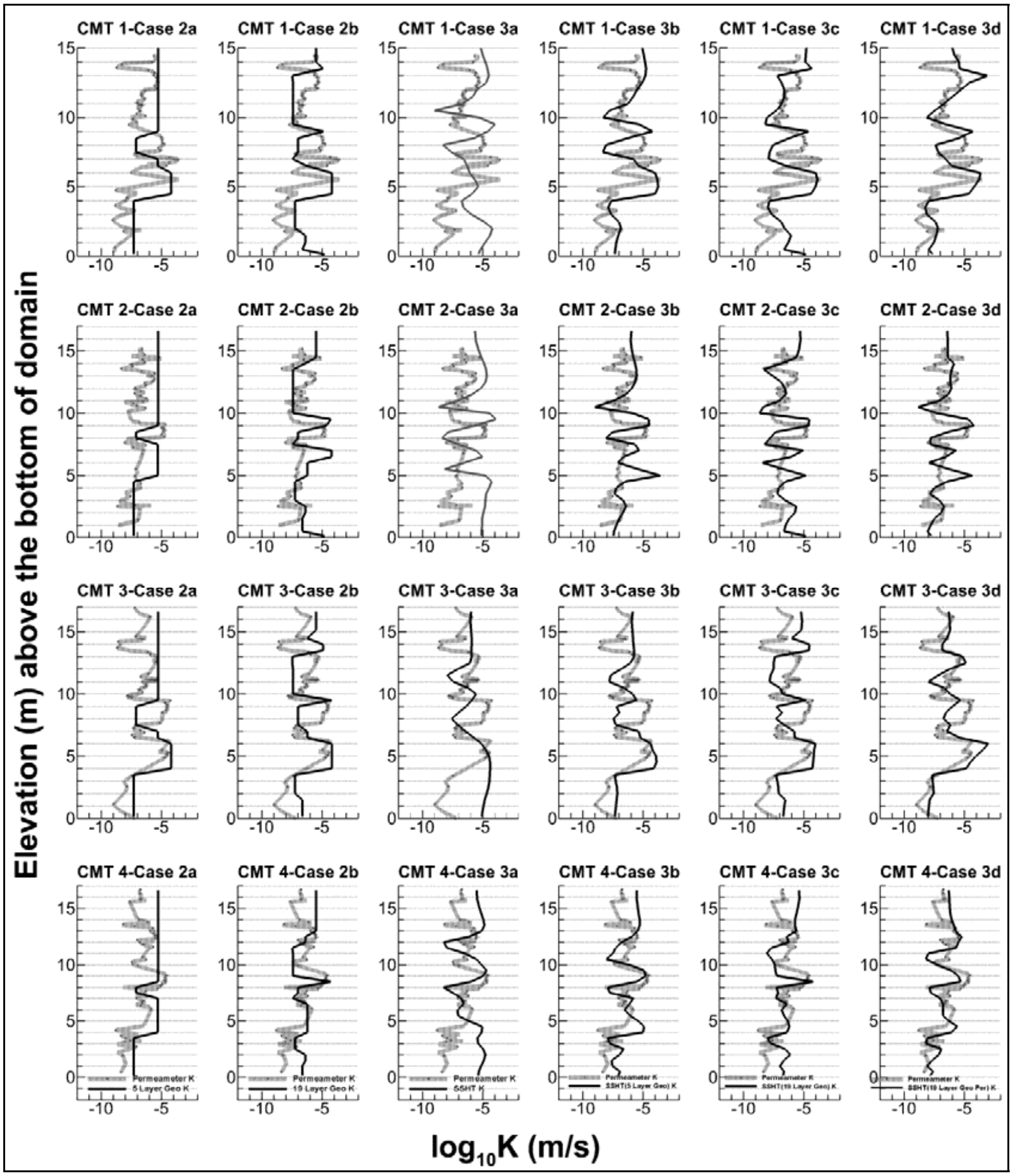


Figure 6-3. Vertical $\log_{10}$K Profiles Along Nine Boreholes of CMT Wells

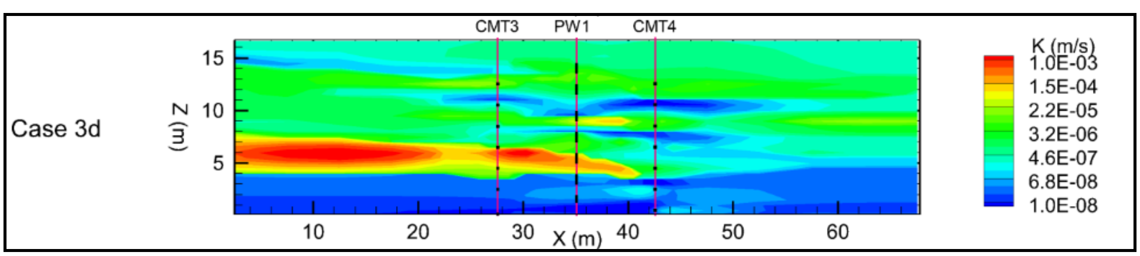


Figure 6-4. K Estimates Along D-D' Cross Section in Figure 4-3

6.3.2 AFP44 Site in Tucson, Arizona

Figure 6-5 shows an overlay map of the spatial distribution of K-values estimated by HT on an aerial photo of the AFP44 site. The results are consistent with the knowledge that more permeable regions (shown in red in the figure) delineated by HT **match the regions with more coarse-grained soils and higher well yield.** The less permeable regions (shown in blue) are consistent with the regions with more fine-grained soils. The low-K region delineated by HT is **consistent with the area where hydraulic fracturing was performed in 2015-2016 to enhance the recovery of chemicals in the fine-grained soils**.

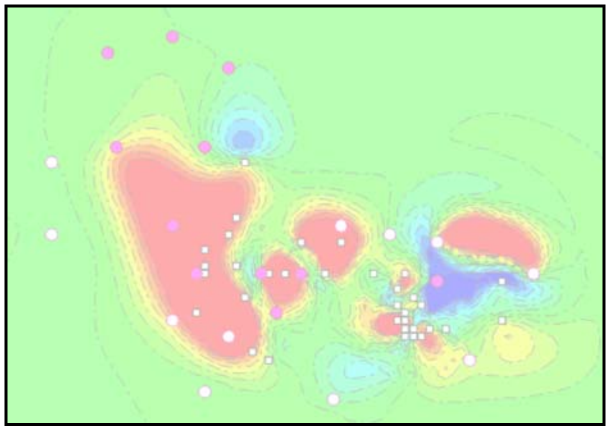


Figure 6-5. Spatial Distribution of K-values Delineated by HT at AFP44 Site

Figure 6-6 shows the **delineated K-field at different resolutions**. It shows that HT produces results at a resolution consistent with the spacing of the wells in the HT survey. If the wells are spaced closer, HT delineates the K-field at higher resolution.

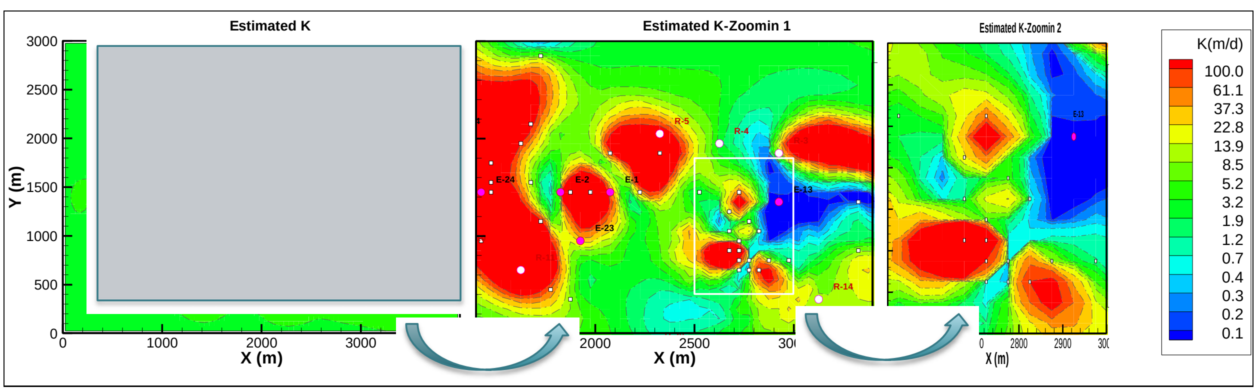


Figure 6-6. Delineated K-field at Different Resolution

The 3-D HT results suggest that there is a thin low K zone (notice that vertical and horizontal axes are not to scale) in the middle of the aquifer (50 ~80 m) and it fades to the north and west directions. This is consistent with the geological description of the pinchout. Moreover, the top low K zone is also consistent with the geological description. Although this comparison is provided only in a qualitative sense, the consistency of geological information and the estimates enhances the credibility of the inverse results.

6.4 PERFORMANCE OBJECTIVE: ILLUSTRATE COST-EFFECTIVENESS OF HT AGAINST CONVENTIONAL TECHNIQUES

The cost-effectiveness of HT depends strongly on whether new wells and water treatment system are needed. The costs of performing HT surveys are the same as the costs to perform conventional pumping tests. The labor costs for performing HT analysis using all HT survey data are similar to the labor costs of performing conventional data analysis.

For large models, more expensive computer systems might be needed if more powerful computers are desirable to reduce computational time. Using the same existing well network and pump-and-treat system, **HT provides hydraulic information in greater details and higher resolution than conventional methods.** To obtain similar levels of detail using conventional methods, more wells and/or other local-scale measurement, such as cone penetrometer test, will be needed.

An existing well network was available at the NCRS. The extracted groundwater did not need to be treated. The disposal of water to the existing storm drain was free. A high-performance computer system was available. For the demonstration at the AFP44 site, the existing well network and pump-and-treat system were used. High-performance computer system was available for the HT inversion. The only costs for conducting the HT site characterization for both sites were just the labor costs for conducting the pumping tests and performing the model inversion.

Although we visited both sites frequently to download the transducer data to perform interim HT model inversion for this project, this amount of activity might not be necessary for other projects if a reduction of expenses is desirable. Transducers can be programmed to record all data until multiple pumping tests are completed, and all the collected data can be analyzed at once to produce a single final model. However, the accumulation of data until all experiments are completed is not a recommended practice. Data should be frequently downloaded and backed up.

6.5 PERFORMANCE OBJECTIVE: ILLUSTRATE THAT HT IS 'USER-FRIENDLY'

HT is a "user-friendly" site characterization technology. HT surveys involve installing new wells, if needed, and performing pumping tests. The skills and equipment needed are the same as those commonly used in conventional site characterization. HT analysis involves compilation of pumping test data and performing model inversion. The input data required for model inversion are the same as the data used in groundwater model development and calibration, such as the input data for parameter estimation using the commonly used software PEST and MODFLOW.

6.6 PERFORMANCE OBJECTIVE: ILLUSTRATE THAT HT IS ABLE TO IDENTIFY LOW-CONDUCTIVITY ZONES

The evaluation described in Section 6.3 has illustrated that **HT is able to delineate low-K zones** consistent with the available lithologic data locally. In addition, it can infer the hydraulic continuity of the low-K regimes in between available lithologic information. It provides information as to whether these regimes are hydraulically functioning as competent barriers. In conjunction with available chemical concentration data, the information is useful for evaluating potential residual sources.

7.0 COST ASSESSMENT

There are two components constituting the total costs of HT site characterization. One component is the **costs of conducting HT surveys** in the field. This includes the costs associated with preparing and performing the field activities for collecting drawdown data from pumping tests. The second component is the **costs of analyzing the data** collected and interpreting the results.

Figure 7-1 conceptually illustrates the logistics of the HT Investigation planning process. The total cost depends on the desirable spatial resolution of the K-field to address the site characterization objectives; whether the existing well network is adequate for monitoring the hydraulic responses to the HT pumping tests; site access and operational constraints; whether onsite treatment system and disposal can be utilized; and the amount and noisiness of the data collected for HT analysis.

Site Characterization Objectives

The specific objectives of a site characterization using HT and the situation at the site dictate the appropriate level of investigation efforts needed and the associated costs. For example, the extent and spatial resolution of the HT investigation for characterizing a paleochannel to support the design of a pump-and-treat containment system would be different from those for delineating pathways to support substrate delivery for enhancing source zone bioremediation.

Spatial Resolution

The desirable spatial resolution of the K- and Ss-fields to be delineated by HT depends on the site characterization objectives and the level of heterogeneity at the site. The number of extraction/injection wells and their pumping rates should be sufficient to generate hydraulic stresses that can be detected with adequate accuracy throughout the area of interest. Well locations should be appropriately selected to reduce costs. The number of monitoring wells, their locations and screen intervals, should be selected to cover the area of interest, and the spacing between wells should be smaller than the desirable length scale of the K- and Ss-fields to be delineated. The more non-redundant hydraulic response data is collected, the smaller the tomogram uncertainty will be.

Existing Well Network

HT investigation is most cost-effective if the existing well network at a site is sufficient, and there is no need to install additional wells. Wells screened in specific short depth intervals would be more preferable. If only long-screened wells are available, it is desirable to select wells with depth-discrete information, such as borehole flowmeter profiles and geophysical logs. If applicable, packers or multilevel liners can be installed to target specific hydrogeologic zones. If additional wells are needed to supplement the existing well network, multilevel/multichannel wells or clustered wells should be considered, as they would provide higher resolution results.

Site Access and Operational Constraints

Site access and operational constraints affect HT data collection. More pressure transducers with larger datalogging memory size can be used to reduce the need for site access and operational interference.

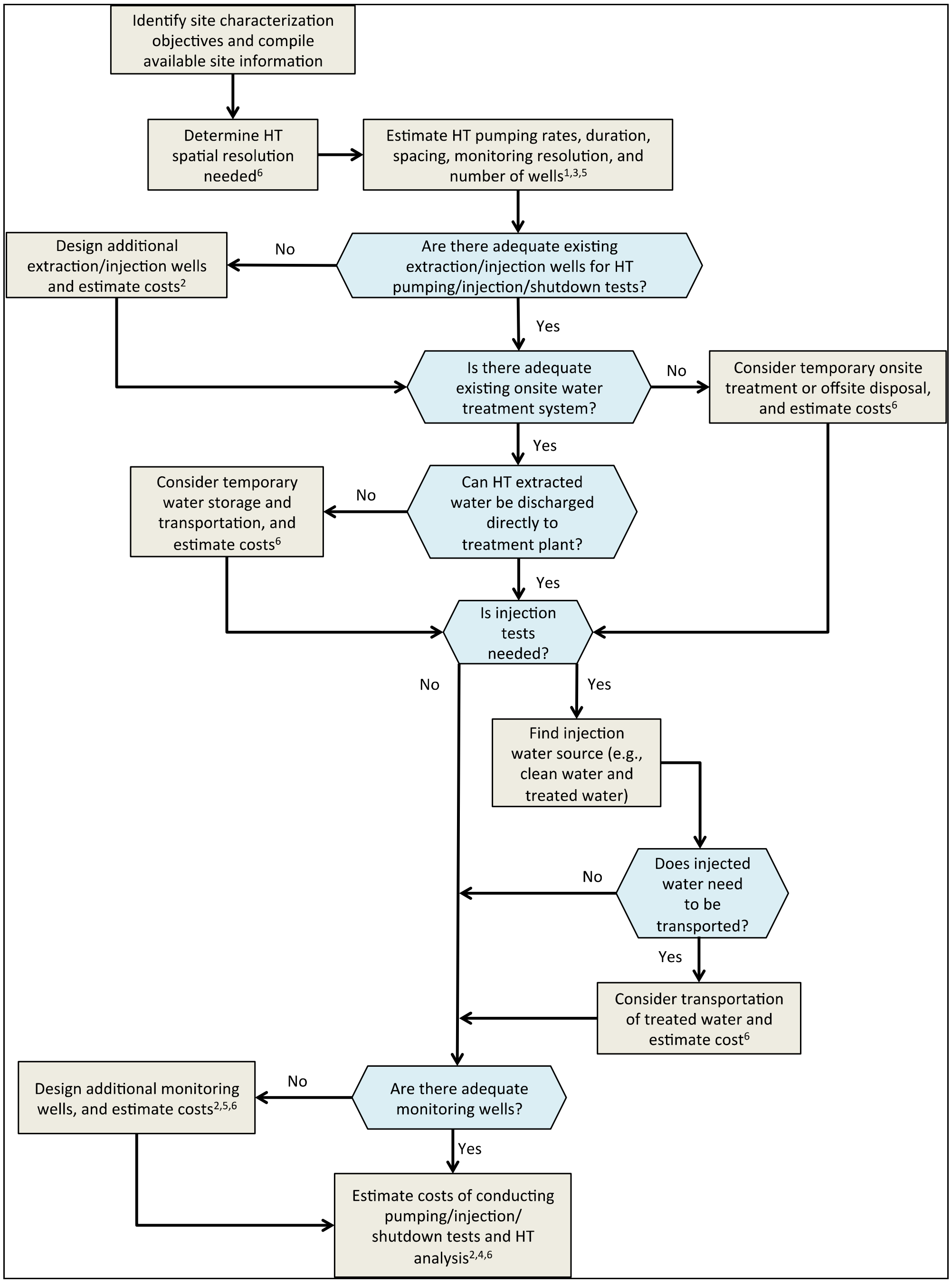


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Figure 7-1. Conceptual Illustration of the Logistics of HT Planning Process

Onsite Treatment and Disposal

The groundwater extracted during HT investigation in chemically impacted zones would require treatment before disposal or re-injection into the subsurface. HT investigation could be more cost-effective if water from extraction wells are directly piped to an onsite treatment system. If the onsite treatment system has sufficient capacity and is available, but direct piping is not feasible, the extracted groundwater needs to be transported to the unit. Temporary storage units, such as water tanks, might be needed. If an onsite treatment unit is unavailable, a temporary treatment unit or off-site disposal might be needed. Alternatively, injection of clean water can be used to induce hydraulic stress. Regulatory requirements may apply in adjudicated basins where water samples need to be tested to confirm that the injected water meets the regulatory water quality criteria.

7.1 COST MODEL

Table 7-1 summarizes the key cost components of conducting the HT site characterization. The first three items are related to conducting HT surveys. The last item is the cost of performing HT analysis.

7.2 COST DRIVERS

Table 7-2 summarizes the cost items and the potential cost drivers for conducting HT site characterization. Installing new wells and treating the extracted groundwater are the major cost drivers. HT site characterization is most cost-effective when it is performed using an existing well network and treatment system. HT can always be readily applicable to sites with existing pump-and-treat systems, since it optimally uses all the information available. As such, the results are the most optimal and unbiased, based on the available information.

7.3 COST ANALYSIS

For a cost comparison, we use a project of similar scale to the NCRS. We considered two approaches for characterizing subsurface heterogeneity: one that relies on detailed borehole data (Approach 1) and another that relies on HT (Approach 2). Where possible, real costs from this study are used, and labor is estimated at approximately $100/hour. Table 7-3 and Table 7-4 summarize the costs for Approaches 1 and 2, respectively.

For Approach 1, we assumed that continuous soils cores are collected during the installation of fully screened wells. This is a slow process, which can add considerable costs to drilling in comparison to the traditional installation of pumping or observation wells. The drilling costs for the five wells totaled $60,000. However, if coring is the only objective, and if wells do not need to be installed, then the costs can be somewhat reduced. Another costly item for Approach 1 is the laboratory permeameter analysis of soil cores, which can be a very slow process when a large number of samples need to be analyzed and when the analysis is undertaken for lower K materials. For our study, the estimated duration for sample analysis is based on the experience of Alexander (2009) who performed the laboratory analysis at the UW. The cost of sample analysis amounted to $100 per sample, or $47,100 for all 471 samples. Actual costs of laboratory permeameter analyses may be higher. The data analysis component included data reduction/ processing ($4,000), geostatistical analysis ($4,000), and report writing ($2,000). The total cost of characterizing the subsurface heterogeneity through the geostatistical analysis of core samples (Approach 1) was $117,100.

For Approach 2, we separated the costs associated with the HT survey and the required equipment that may be reused. As in Approach 1, drilling for Approach 2 is a slow process because of the installation of multi-screen wells. Here, drilling is assumed to be complete without the collection of soil cores. A significant amount of cost is added to the drilling by alternating the backfilling of sand pack and bentonite in order to prevent short-circuiting between adjacent pumping and/or observation intervals. The total estimated cost for drilling is approximately $60,000 and is based on the cost of installing all five wells.

Table 7-1. Cost Model for HT Site Characterization

Cost Element	Cost Components	Data Tracked During the Demonstration
Installation of Extraction/Injection Wells and Monitoring Wells	Unit: $ per linear foot of well Data requirements: • Number of wells, their diameters, depths, and screen intervals • Recommended installation method • Mobilization cost • Time required, personnel required, and associated labor • Materials	Not available (NA; existing wells were used)
Groundwater Extraction, Treatment, and Disposal	Unit: • $ per pump • $ per volume of groundwater extracted • $ per operation day Data requirements: • Number of pumping tests, pumping rates, lift, and duration • Groundwater storage method • Groundwater treatment and disposal method • Time required, personnel required, and associated labor • Materials • Analytical laboratory costs	NA (existing pump-and-treat system was used at AFP44; no need to treat extracted groundwater at NCRS)
Pumping Tests	Unit: • $ per day Data requirements: • Number of pumping tests, number of wells to be monitored, and duration • Pressure transducers • Time required, personnel required, and associated labor • Materials	• Pump rates over time • Hydraulic head over time • Atmospheric pressure over time (for correction of hydraulic head)
Compilation of Pumping Test Data and HT Model Inversion	Unit: • $ per day Data requirements: • Number of pressure transducers • Resolution of HT inversion model	NA (the level of details and experimentation of different analysis approaches was more involved than normal application)

Table 7-2. Cost Items and Cost Drivers for HT Site Characterization

Cost Items	Cost Factors	Remarks
Extraction/injection well network: wells and pumps	Availability of existing wells; Number of new wells, their well sizes and depths; Ease of access; Permitting; Pump size and packers, if needed	Potential cost driver if new wells are needed
Monitoring well network	Availability of existing wells; Number of new wells and depths; Ease of access; Permitting	Expensive, but less costly than extraction wells.
Extracted water disposal	Availability of on-site treatment; extraction rate and duration; storage and treatment costs; transportation costs if applicable	Potentially expensive
Transducers	Number of transducers; Type, size, and storage	Relatively inexpensive if diameter of well/sounding tube >= 2”
Sequential HT aquifer tests	Availability of site staff	Relatively inexpensive if site staff is available
HT data analysis	Resolution needed; 2D versus 3D; steady state versus transient	Relatively inexpensive

Costs to conduct HT include the man hours required to perform multiple pumping tests ($12,000), data processing ($8,000), the inverse modeling of the test results ($12,000), and reporting ($2,000). The costs of conducting HT minus the equipment costs resulted in $94,000. Therefore, we see that Approaches 1 and 2 are comparable in terms of costs if the equipment costs for HT are not accounted for.

Equipment costs include the pressure transducers ($30,000), the CMT systems ($5,000), FLUTe liners with five pressure transducers each ($36,000), a double-packer system with a submersible pump ($5,000), a data acquisition system ($8,000), and a high-end workstation or a PC-cluster ($20,000). The equipment costs add up to $104,000; however, many of these items can be reused, which we assume will remain at the site upon completion of the survey.

While these estimates are very approximate, they do suggest that implementing HT can be cost-effective if one considers the equipment as a separate cost item, some of which can be reused in other projects. The same can be said for the computer cluster used for running the inverse model. Most importantly, it has been demonstrated that HT significantly improved predictions of drawdowns when compared to conventional methods. The reliance on pumping test data using HT, as opposed to permeameter data, may also be another reason why HT performed better than the traditional geostatistics approach (i.e., kriging) (see Illman et al., 2012), as small-scale samples can be disturbed and core recovery is not always complete.

Table 7-3. Cost Estimate for Heterogeneity Characterization Relying on Point Data

Detailed Characterization	Estimated Costs
1. Drilling (with complete core collection)	$60,000
2. Permeameter analysis (471 samples @ 1 sample/hour)	$47,100
3. Data analysis	
Data Processing (1 week)	$4,000
Geostatistical analysis (1 week)	$4,000
Reporting (0.5 weeks)	$2,000
Total (1+2+3)	**$117,000**

Table 7-4. Cost Estimate for Performing HT

Transient HT	Estimated Costs
1. Drilling (with complete core collection)	$60,000
2. Conducting 4 x 24 hours pumping tests	$12,100
3. Data analysis	
Data Processing (2 weeks)	$8,000
Inverse modeling (3 weeks)	$12,000
Reporting (0.5 week)	$2,000
4. Subtotal (1+2+3)	$94,000
Capital Costs	**Estimated Costs**
5. Instrumentation	
Pressure transducers (28 CMT, 6 for 2" wells)	$30,000
CMT systems	$5,000
FLUTe liners (with five transducers each)	$36,000
Pump-Packer system	$5,000
Data acquisition system	$8,000
6. PC cluster for modeling	$20,000
7. Subtotal capital costs (5+6)	$104,000
Total (4+7)	**$198,000**

Regardless of the choice in characterization method, we contend that improved site characterization before implementing remediation systems will lead to more efficient and effective clean-up operations. Thus, the costs spent upfront to accurately characterize the site should minimize issues that could arise later due to poor site characterization.

8.0 IMPLEMENTATION ISSUES

8.1 HT INVESTIGATION PLANNING

Figure 7-1 shows a flowchart conceptually illustrating the logistics of the planning process for HT Investigation. Consider specific site characterization objectives and site situation. After setting the required pumping well spacing, the number and location of potential new pumping wells have to be determined. The handling of the extracted water has to be accounted for. If the on-site water treatment system is unavailable or unsuitable for the extracted water, temporary storage and transportation options should be evaluated, considering the pumping rates and durations required for showing sufficient drawdown responses. If injection tests are required for the characterization, a suitable source of injection water, such as clean or treated water, needs to be found and its transportation planned accordingly. Depending on the spacing of the existing monitoring well network, the number and location of new monitoring wells must also be determined.

8.2 POTENTIAL REGULATIONS

If additional wells are needed, and especially if they need to be installed in areas with high chemical concentration, pertinent regulatory approval and permits might be required. This is a similar issue with conventional well installation. If the HT pumping tests involve groundwater extraction, pumping permits might be required. In addition, permits for the discharge to on-site or off-site treatment systems need to be acquired. Depending on the application process, extraction water sampling might be necessary. Similarly, permits might have to be obtained for water injection, with a potential sampling of the injection water.

8.3 CONCERNS, RESERVATIONS, AND DECISION-MAKING FACTORS

The key factors to be considered in making a decision on whether HT is appropriate for a site include cost-effectiveness, timing, duration, background hydraulic stresses, and chemical mobilization. The cost-effectiveness depends on the appropriate number of wells, which is dictated by the spatial resolution needed to meet the objectives and whether existing wells and treatment system are adequate. If existing wells and treatment system can be utilized, the costs associated with HT is minimal. Since HT relies primarily on hydraulic response data, it is best applicable to sites with known background hydraulic information, such as presence of other pumping wells and water-level fluctuations. In addition, water level changes due to HT pumping tests might mobilize chemicals during the tests. The duration of the pumping tests is usually short, thus chemical movement is typically small. However, if the aquifer is very permeable, a high pumping rate might be required to induce measurable hydraulic signals. On the other hand, if the aquifer is relatively impermeable, the well yield might be small, and longer HT pumping test duration might be needed.

8.4 RELEVANT PROCUREMENT ISSUES

Standard commercial equipment for groundwater extraction, injection, and monitoring, such as pumps, monitoring wells, liners, packers, and pressure transducers, is suitable for HT. For HT analysis, adequate computational power is needed, possibly in the form of computing clusters.

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